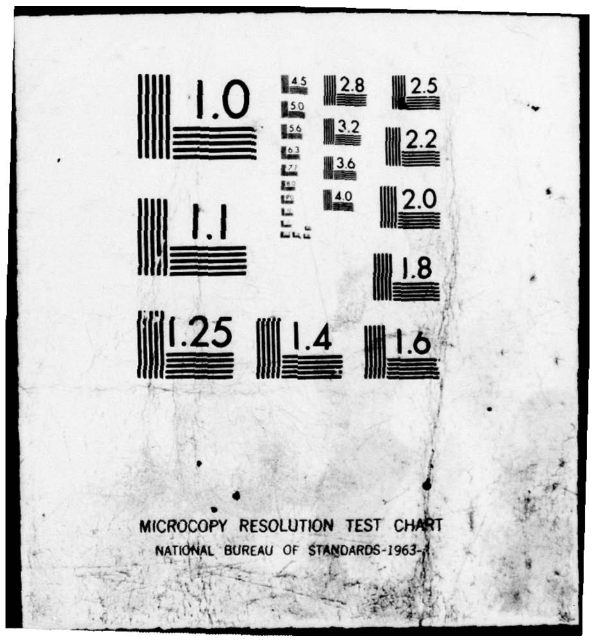
AD-A077 709   ARMY MILITARY PERSONNEL CENTER ALEXANDRIA VA   F/G 8/9
THE STATE OF THE ART OF EROSION AND SEDIMENT CONTROL FOR SURFAC--ETC(U
NOV 79   J L GILBREATH

UNCLASSIFIED   NL

1 OF 2
AD
A077709


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

LEVEL II — 2

AD A077709

THE STATE OF THE ART OF EROSION AND SEDIMENT CONTROL FOR SURFACE MINED AREAS

JOSEPH L. GILBREATH

6

The State of the Art of Erosion and Sediment Control for Surface Mined Areas

10
Joseph L. Gilbreath, Captain
HQDA, MILPERCEN (DAPC-OPP-E)
200 Stovall Street
Alexandria, Va 22332

9 11

Final report, 15 November 1979

12 136

A thesis submitted to The Ohio State University, Columbus, Ohio, in partial fulfillment of the requirements for the Degree Master of Science of Civil Engineering.

391191

THESIS ABSTRACT

THE OHIO STATE UNIVERSITY
GRADUATE SCHOOL
(Please type.)

NAME: Joseph L. Gilbreath QUARTER/YEAR: Autumn/1979

DEPARTMENT: Civil Engineering DEGREE: Master of Science

TITLE OF THESIS: The State of the Art of Erosion and Sediment Control for Surface Mined Areas

Summarize in the space below the purpose and principal conclusions of your thesis.

This thesis attempts to define the State of the Art of sediment and erosion control for surface mined areas with emphasis on sediment ponds. Additionally, pertinent hydrologic aspects, sediment characteristics, and the erosion processes are briefly reviewed. Consideration is given to the uses of computer models as design or analysis tools. Finally, the thesis is summarized in tabular form providing a convenient index for all referenced material. Also included in the last chapter is a list of current research and a list of needed research, and the author's conclusions and recommendations.

Vincent T. [illegible]
Adviser's Signature

B

THE STATE OF THE ART
OF EROSION AND SEDIMENT CONTROL
FOR SURFACE MINED AREAS

A Thesis

Presented in Partial Fulfillment of the Requirements
for the Degree Master of Science of Civil Engineering

by

Joseph L. Gilbreath, B.S.

The Ohio State University

1979

Approved by

Vincent P. Ricca
Advisor
Department of Civil Engineering

ACKNOWLEDGEMENTS

I would like to acknowledge and thank the United States Army for its financial support in the form of a fully funded graduate school fellowship. Additionally, I would like to thank the Mining and Mineral Resource Research Institute of The Ohio State University for its financial assistance.

I wish to express my sincere appreciation to Dr. Vincent T. Ricca, my graduate advisor for his guidance and inspiration throughout my undergraduate and graduate work.

I would also like to thank the other members of my reading committee, Dr. Keith W. Bedford and Dr. Calvin J. Konya, for reviewing my thesis and for providing helpful comments.

Appreciation is extended to all the individuals in universities, government agencies and private practice who willingly provided me with pertinent information throughout my study.

I owe a special thanks to my sister, Cathy, for her assistance in preparing and typing the draft and final copies of this thesis. Her cheerful willingness and long hours of work were essential in meeting the final deadlines.

Finally, I would like to acknowledge the love, support and encouragement which I have always received from my parents, sister, and fiancee. I therefore dedicate this thesis to Mom, Dad, Cathy and Patricia Lee.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

BACKGROUND REVIEW

Population growth, the increase in energy demand per capita, recent public dissatisfaction with nuclear energy, and reductions in foreign oil imports, all combine to intensify the energy crisis experienced by the U.S. today. Rilely[1] reports that in this century, the U.S. doubles its power consumption every decade. Jones[2] predicts that consumption of electrical power will rise from 1,550 billion kwh in 1970 to 3,035 billion kwh in 1980, while Dunham et al.[3] predicts the per capita consumption of electricity will climb from 7,800 kwh in 1971 to 32,000 kwh by 2000.

In light of the difficulties presently faced in using nuclear power, and of obtaining oil, it is reasonable to assume that coal will be heavily relied upon to help meet the rising energy demand. Dunham[3] estimates that the U.S. has 3 trillion tons (2.73×10^{12} MT) of domestic coal of which 200 billion tons (181.8×10^{9} MT) can be economically mined with present technology. In a study conducted by the National Academy of Engineering, it was concluded that coal production will need to be increased from an estimated 675 million tons (6.13×10^{8} MT) in 1974 (Overton[4]) to 1.2 billion tons (1.09×10^{9} MT) per year by 1985 (Bagge[5]). Poe[6] indicates that this figure may be as high as 2.6 billion tons (2.36×10^{9} MT) if imports of gas and oil are restricted and may rise as high as 4 billion tons (3.63×10^{9} MT) by 2000.

As in the use of nuclear power and oil, coal as a source of energy is not problem free. One of the major problems now facing the coal industry is the polluting of streams and rivers by sediment which is eroded from the land disturbed during surface mining operations. Of all the coal used in 1974, it is estimated that over 50% was extracted by surface mining (Overton[4]). In 1970, Collier et al.[7] reported on a study aimed at evaluating the hydrologic impact of surface mining. The study involved Beaver Creek in south-central Kentucky, and it revealed that the surface mined watersheds yielded an average of 1900 tons of sediment per square mile (666.9 MT/km^2) per year during the four years following completion of surface mining operations. This is compared

to 25 tons per square mile (8.78 MT/km^2) per year for a similar unmined watershed. In 1971, Curtis[8] reported on a study of the Leatherwood Creek basin in Breathitt County, Kentucky. It was found that suspended solids (SS) concentrations in three watersheds within the Leatherwood Creek basin increased substantially during the active mining periods. The highest SS concentrations for each of the three watersheds were recorded as 46,400, 26,900, and 9,600 parts per million (ppm), compared to SS concentrations of 150 ppm in adjacent undisturbed watersheds. Many more examples of a similar nature can be found in the current literature. It is sufficient to say that surface mining greatly increases the suspended solids concentrations in the streams which receive runoff from the disturbed land.

It is estimated that from all sources, for instance, agriculture, forests, construction sites, roadways, surface mining, etc., a total of 3.6 billion metric tons of sediment is eroded each year in the United States. Of this, about 1.8 billion metric tons enter streams and rivers (Highfill[9]).

The pollution of water by sediment is a multifaceted phenomenon. Besides being the major water pollutant by weight and volume, sediment has been found to be a carrier and storage agent of pesticide residue, adsorbed phosphorus, nitrogen and other organic compounds, and pathogenic bacteria and viruses[10]. Furthermore, sediment affects the biota in several ways. Silt and fine sands can accumulate on stream beds and eliminate spawning grounds as well as the habitat of aquatic insects which form the food supply of fish. Certain types of fish experience gill and breathing structure injuries due to the suspended sediment in the water. Additionally, suspended sediment restricts light penetration which alters the water temperature, and reduces photosynthesis both of which adversely affects the entire biota. Sediment deposits in streams and channels reduce the flow carrying capacities and thereby increase the risks of flooding. Deposits in harbors, reservoirs, and navigable waterways require costly dredging operations. Turbid water increases water treatment plant costs and reduces pump and turbine life. Finally, sediment polluted water reduces its aesthetic and recreational value.[11,12]

In 1977, Heft[13] reported that the annual loss in Ohio alone due to sediment amounts to $94,386,000. This loss includes the cost of dredging sediment from harbors on Lake Erie, sediment removal from drainage channels and highway ditches, sediment damages to inland lakes and reservoirs, treatment and filtering of water for municipal and industrial use, sediment, fertilizer and nutrient loss from

agricultural cropland and loss of fish and other wildlife.

It should be noted however, that although man has increased the sediment load in our waterways, erosion and sediment are natural phenomena which existed prior to man disturbing the earth's surface. It is not therefore desirable to completely eliminate sediment in all streams and rivers. Gessler[11] discusses an interesting approach to establishing sediment standards in rivers. He notes that the different disciplines concerned about sediment (ie. conservationist, agronomist, hydrologist, biologist, fluvial-morphologist) view it from different perspectives and that each group's interests need to be considered when setting standards. He also discusses the dilemma of determining the "natural" sediment load of a waterway. Without becoming involved in lengthy discussions, it is desired to point out two items. One is that the setting of standards should not be arbitrary, and the second is that completely sediment free water is not necessarily desirable.

At present, the primary concern of coal operators is the recently enacted Federal regulations governing surface mining operations. Although coal operators will be governed by state regulations, the state regulations must meet or exceed the standards set by the Federal regulations. State standards are not expected to exceed those presently set by the Federal regulations. (At the time of this writing, most state permanent regulations are still unpublished.) The items of the Federal regulations that directly affect coal operators' sediment control programs are quoted here from the Federal Register.[14]

1) "Para. 816.42 Hydrologic balance: Water quality standards and effluent limitations.

   (a)(1) All surface drainage from the disturbed area, including disturbed areas that have been graded, seeded, or planted, shall be passed through a sedimentation pond or a series of sedimentation ponds before leav- the permit area."

2) Para. 816.42

   "(a)(7) Discharges of water from areas disturbed by surface mining activities shall be made in compliance with all Federal and State laws and regulations and, at a minimum, the following numerical effluent limitation:"

Total suspended solids - maximum allowable 70.0 (mg/l)
- average of daily values for 30 consecutive discharge days 35 (mg/l)

"(b) A discharge from the disturbed areas is not subject to the effluent limitations of this Section, if-

(1) The discharge is demonstrated by the discharger to have resulted from a precipitation event equal to or larger than a 10-year, 24-hour precipitation event; and

(2) The discharge is from facilities designed, constructed, and maintained in accordance with the requirements of this Part."

In summary thus far, it is anticipated that coal will play an increasing important role in easing the energy crisis. Surface mining operations, extensively used by the coal industry, dramatically increases erosion and sedimentation. The pollution of our waterways by this enormous sediment increase is both serious and costly. In an effort to curb this increase in sediment load caused in part by the mining industry, the Federal government has passed regulations which require mine operators to employ sediment control measures.

PURPOSE OF THESIS

It is the objective of this thesis to determine the "State of the Art" of sediment control in surface mining. Knowledge of the State of the Art will be an aid in directing future research to improve the effectiveness of sediment control methods.

Current methods and techniques of sediment control were reviewed, but primary emphasis was placed on sediment ponds. References for the techniques discussed are given; but, details and design criteria are not catalogued here.

In addition to determining the State of the Art, a list of the known current research in this area was compiled. Also compiled is a list of research needs for the further development of methods to effectively control erosion and sediment in surface mining operations.

APPROACH

To determine the "State of the Art," a literature search was conducted and selected government agencies, universities and engineering consultants were contacted. (A bibliography as well as a list of agencies and institutes contacted can be found in the appendix.) There exists few published articles about sediment control specifically for surface mining. However, many articles can be found about erosion and sediment control in the areas of agriculture, highway and residential construction, and water and sewage treatment. Although each area has its own particular problems in sediment control, the major principles involved are universal to all.

THESIS CONTENT

This thesis has been organized into six chapters. Following this introductory chapter, Chapter II reviews hydrologic terms and tools, sediment properties and the erosion processes. In Chapter III, erosion and sediment controls, except for sediment ponds, are reviewed. Chapter IV discusses in detail the design aspects of sediment ponds. Chapter V reviews some of the types of computer programs which can aid in designing sediment ponds. Finally, Chapter VI summarizes the "State of the Art" of erosion and sediment control, lists ongoing research in the area and recommends areas for further research.

CHAPTER II

HYDROLOGY - SEDIMENT - EROSION

INTRODUCTION

The purpose of this chapter is to review the processes and terminology required in sediment control studies. As suggested by the title, this chapter will be divided into the three areas of hydrology, sediment and erosion.

The reason for reviewing hydrology is that the agent of interest, responsible for soil particle detachment and transport is rainfall and its subsequent runoff. (Although wind is also an agent, it is not included within the scope of this study.) If the erosion/sediment problem is to be controlled, the hydrologic processes which cause the erosion, must be understood. Furthermore, government regulations are written using specifications which require some knowledge of hydrologic concepts and terminology. Only those hydrologic processes and tools which are commonly used in the study of erosion and sediment control will be reviewed. These are all fairly well established and documented within the hydrology field, and the discussions here therefore will be general and brief, with references for the reader desiring more detail.

While studying the processes of erosion and sedimentation, it is both helpful and necessary to know the properties and characteristics of the soil particles which are being eroded and transported. The physical and chemical properties of the soil particles determine their erodibility, how they will be transported and finally if and how they will be deposited. Consequently, it is necessary to know the sediment properties and characteristics in order to predict the amount of erosion, the yield, the trap efficiency of sediment ponds and sediment storage volume requirements. Virtually every aspect of sediment control relies on the knowledge of soil particle properties. An attempt will be made here to summarize the latest known facts about the physical properties and characteristics of sediment. Although the chemical properties of sediment will determine to what extent sediment acts as a transporting agent of other pollutants, the chemical properties reviewed here will be limited to those which affect coagulation and flocculation.

The final topic of this chapter is erosion. This process by which sediment is produced is important to understand so that measures can be devised and employed to reduce the initial production of sediment. Furthermore, a knowledge of the erosion process will enable predictions to be made of the amount of sediment which will be produced and which will need to be trapped and stored in sediment ponds. Qualitative knowledge about erosion processes is fairly well established; however, the quantitative information of measurement and prediction of soil erosion (particularly in surface mined areas) is still pretty much a State of the Art. A brief overview of the qualitative processes will be presented along with references for those desiring more details. Also, the relevant methods for measuring and predicting erosion quantitatively which have been found in the literature will be summarized.

HYDROLOGY

The Federal regulations[14] stipulate that the sediment pond effluent standards need not be met for a particular storm if the discharger can demonstrate that the precipitation event is equal to or exceeds a 10-year, 24-hour precipitation event. Elsewhere in the Federal regulations, it is specified that for a permanent diversion the channel, bank and flood-plain configuration must be adequate to safely pass a 100-year, 24-hour precipitation event. The terminology of "x-year, y-hour" is frequently used by hydrologists in frequency analysis. The "x-year" is known as the return period, and the "y-hour" is the duration of the storm in hours.

The return period is used to describe both precipitation events as well as streamflow events. The discussion here will be limited to rainfall events; however, the same principle of probabilities holds for streamflow events. A return period of "x-year" signifies an event which is expected to occur once in x years, or has the probability of $1/x$ of occurring in a particular year. When speaking of precipitation events, a return period is associated with a particular magnitude. For a storm to have a given return period, its magnitude must equal or exceed the magnitude associated with that return period. For a given return period, the associated storm magnitude will vary from one geographic location to another.

Storm magnitudes are measured by rainfall intensity in inches per hour. Rainfall, however, does not occur in nature with uniform intensities. Generally a rainfall will begin

with a low intensity, increase to its maximum intensity and then taper off gradually. Thus when speaking of the intensity of a storm, it is necessary to refer to the average intensity. Another measurement of a storm is its length in time or its duration. Obviously two storms of equal average intensity, but of different duration will produce different amounts of total rainfall. That is the reason it is necessary to specify both the return period and the duration to describe magnitude when defining design criteria for a particular location.

For a given geographical location a set of frequency-intensity-duration curves can be constructed from past rainfall data. Figure 1 shows a typical rainfall intensity-duration-frequency curve. This particular set of curves is for the Sandusky, Ohio area. From a set of curves like these, one can easily determine the average intensity of a storm of given frequency, duration and location.

In order to determine return periods for a given location, it is necessary to have many years of records for the event of interest. Generally, rainfall data is more readily available than is streamflow data. In fact, streamflow data for small streams is rarely available in sufficient quantity. Furthermore, land use will generally affect streamflow data whereas rainfall is not affected. Therefore, it is convenient to talk about design criteria in terms of precipitation events as opposed to streamflow. However in the design of hydraulic structures, the precipitation event must be transformed, by processing it through the watershed, into usable streamflow data prior to design work.

In the design of hydraulic structures, more information is needed about a precipitation event than just the total volume of water. The effect of 1 inch of rainfall which falls in one hour will vary greatly from the effect of 1 inch of rainfall which is received over a span of twelve hours. The technique used to graphically portray the time history of a precipitation event is called a hyetograph. To construct a hyetograph, the rainfall event is divided into small equal time steps usually about five minutes in length. The intensity of the rainfall is averaged over each time space and then plotted against time as shown in Figure 2.

A particular recorded storm is sometimes selected as a design storm, for which the hydraulic structure is designed to safely handle. An alternative approach is to develop a synthetic hyetograph from the intensity-duration-frequency curve for the desired frequency and duration. One example of synthetic hyetograph construction is given by Haan and Barfield[16]. They also discuss two other methods of developing synthetic hyetographs, the U.S. Soil Conservation

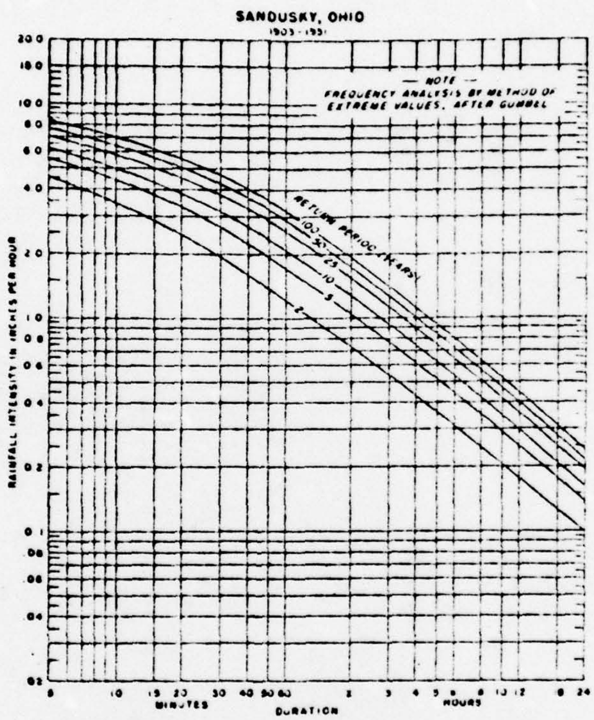


Figure 1. Rainfall Intensity-Duration-Frequency Curve for the Sandusky, Ohio Area
(taken from Reference 15)

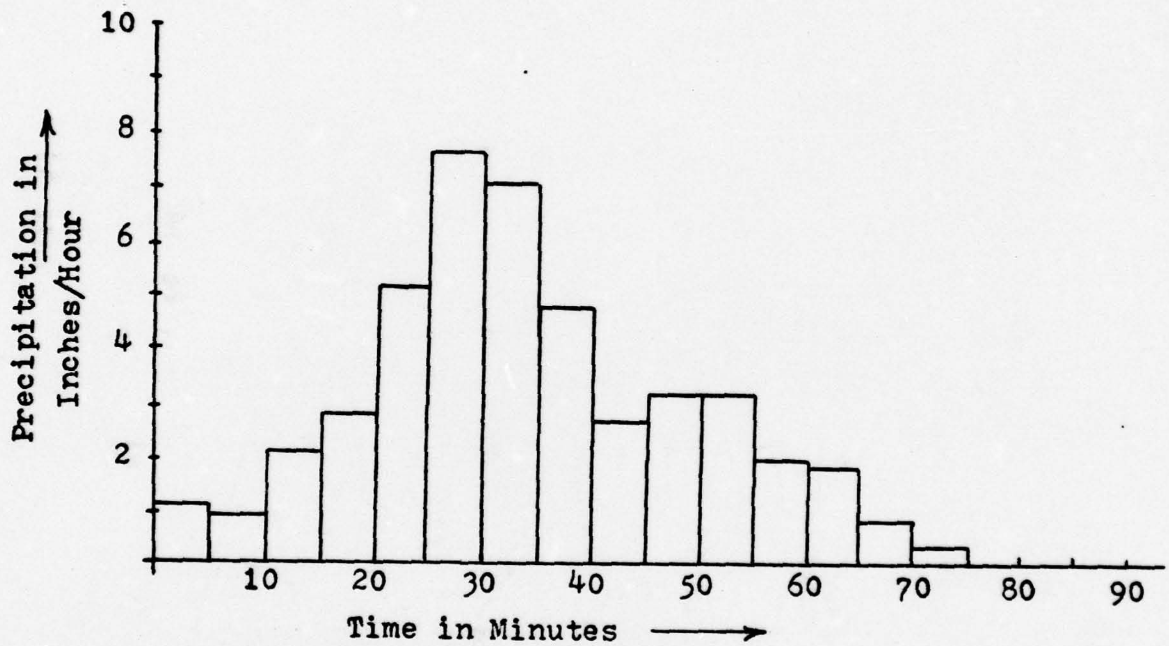


Figure 2. Rainfall Hyetograph

Service (SCS) method and the Huff method. The SCS method is considered by Haan and Barfield as the simplest and most consistent. For a comparison of these three methods, the reader is referred to reference 16. Regardless of the method of obtaining the design hyetograph, it must be transformed into a hydrograph prior to design work.

A hydrograph is the plot of flow rate against time. Haan and Barfield further state that, "The hydrograph is the result of a particular effective rainfall hyetograph as modified by basin flow characteristics."[16] Effective rainfall is the stormwater runoff or in other words, the total rainfall minus abstractions, in which the abstractions are losses of rainfall which do not result in runoff. Abstractions include evaporation, infiltration, interception and surface storage. Hydrographs differ from hyetographs in that the hyetographs are the time history of rainfall intensity, where hydrographs are the time history of rainfall runoff passing a particular point of interest. The time history of the rate of flow is dependent on the hyetograpy, the abstractions and the flow characteristics of the basin.

Of the four sources of abstractions mentioned above, only three are usually considered when generating hydrographs from hyetographs. Usually evaporation is neglected. This is because design hyetographs are usually of high intensity short duration storms; where evaporation is practically nonexistent, especially in comparison to the rainfall volume.

Infiltration is perhaps the largest source of rainfall loss. In generating hydrographs, it is the rate of infiltration which is required. Infiltration rates for most soils vary with time. Frequently Horton's Equation[17] is used to describe infiltration rates. Without going into details here, infiltration rates decrease rapidly after the beginning of a rain and then asymptotically approach a constant infiltration rate, usually 1.5 to 2 hours after the beginning of the rain. Infiltration rates are a function of the antecedent soil moisture conditions, soil type, subsoil type, slope, ground cover and rainfall intensity.

Surface storage abstractions refer to the water that fills and is trapped in small surface depressions. This water eventually infiltrates or evaporates but never flows overland to become runoff. Actual measurement is extremely difficult and there seems to be no universally accepted method.

The third and last source of abstractions to be mentioned here is interception. Like surface storage, interception is extremely difficult to measure and is often

neglected or combined with one of the other sources of abstractions. Physically, interception is the catching and the storing of rainfall on the surface of vegetative covers. The interception capacity is usually satisfied early in the storm. The way that each of these abstractions are handled will vary depending on the method used to develop the hydrograph. The references for the models discussed in Chapter V will provide the details on how these abstractions can be computed.

Thus far hyetographs and abstractions have been discussed. Before a hydrograph can be generated however, the flow characteristics of the basin must be understood. The hyetograph considers the time history of the water delivered to the watershed by rainfall and the abstractions consider the reductions of the amount of rainfall which will be available for runoff. Now it is the basin flow characteristics which will determine how the water will be routed over the watershed and delivered to the point where the hydrograph is desired.

It is necessary to know how long it will take to drain, or route the runoff through the watershed and past the point of interest. There are many factors which will affect the travel time. First and most obvious is the distance the water has to travel. In developing hydrographs, the watershed is generally divided into areas having equal ranges of travel time. That is for instance, if the watershed is to be analyzed in time increments of say three minutes, the area having travel times of 0 - 3 minutes will be delineated from those having travel times of 3 - 6 minutes, 6 - 9 minutes, etc. In order to do this, flow distances must be measured and flow velocities must be computed. Slope, ground cover, depth of flow and whether the water is flowing overland or in channels are all factors affecting flow velocity. These factors, or flow characteristics, will be different for each watershed. It is common practice to compute travel times by dividing the watershed into areas of similar topography and cover, and then compute average slopes, average distances and average cover factors. An average velocity and travel time can then be computed for each area. The hyhetograph is then applied to the watershed, abstractions are subtracted and the flow is routed through the basin. The details of a conception as just described is given by Haan and Barfield.[16] They also discuss other methods to construct hydrographs, such as the Santa Barbara Urban Hydrograph Method, a hydrodynamic model the SCS Hydrograph Procedure, and the unit hydrograph approach.

The unit hydrograph approach will be briefly explained here. A unit hydrograph reflects the watershed's flow characteristics. It is a hydrograph developed from a unit

of rainfall over the entire watershed applied at an equal rate for a specified duration. It is possible to convert a unit hydrograph for a specific duration to another unit hydrograph of different duration. For the details on this, see reference 18.

Given a unit hydrograph of a particular duration, a hydrograph for a rainfall of any intensity with the same duration can be constructed by simple proportions. For example, a unit hydrograph represents 1 inch (2.54 cm) of rainfall over a specified duration. If a hydrograph for a 2 inch (5.08 cm) rainfall with the same duration is desired, simply double the values for the flow rates on the unit hydrograph.

Hydrographs can be developed for more complex rainfall events also. To do this, unit hydrographs of duration equal to the time steps of the hyetrograph are used to portray the runoff for each time step independently. The unit hydrographs must reflect the average intensity of their respective time step of the hyetograph. Each of these hydrographs are plotted on the same graph, staggering them according to their relative position in the storm. Superimposing all of the hydrographs will give the total hydrograph for the entire complex storm. For more details on this method, the reader is referred to Reference 16, or any basic book on hydrology.

Computer models have also been developed to produce runoff hydrographs. Chapter V will discuss these computer models in more detail.

Figure 3 shows the basic hydrograph terminology. The area under a hydrograph represents the volume of water that has passed the point of interest during the total time duration of the hydrograph or base time. The highest point or peak of the hydrograph represents the peak discharge rate. The time from the beginning of the hydrograph to the peak discharge, t_p, is called time to peak. The time from the center of mass of the effective rainfall to the peak of the runoff hydrograph, t_l, is called lag time.

When talking about sediment basins, two hydrographs are considered: the inflow hydrograph and the outflow hydrograph. They describe the time rate of flow into and out of the basin respectively. By their design, sediment basins detain or store part of the flow for varying lengths of time. Thus the outflow hydrograph will have a reduced peak but extended time base. Detention time is the time that water is detained in the basin. This time varies throughout the routing of the runoff event. In order to have one average detention time for a given basin and storm, detention time

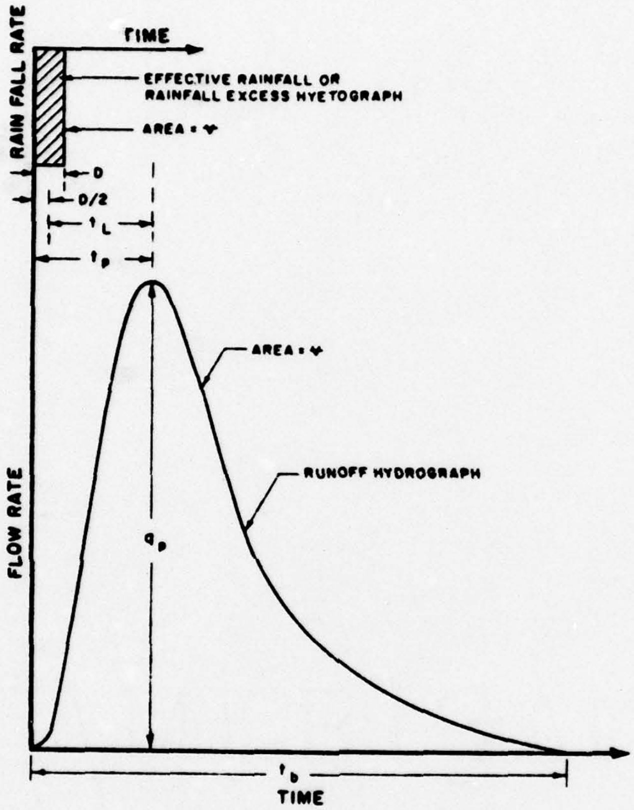


Figure 3. Hydrograph Terminology
(taken from Haan and Barfield[16])

is sometimes defined as, the time between the centroids of the inflow and outflow hydrographs. This is the definition used in the Federal regulations.

Another tool which has recently appeared in the literature but which has yet to receive wide acceptance or use is the sediment graph. Sediment graphs are a time history of sediment rates. Basically a sediment graph is the product of a hydrograph and the sediment concentration where the concentrations vary with time but not necessarily at the same rate as the flow rate. Without sediment graphs, only an average sediment concentration can be assumed throughout the storm duration. This obviously hides the maximum sediment concentration which may be important in terms of water quality. In a report by Willis et al.[19], 50% of the sediment discharge from the Coles Creek and Buffalo River in southwest Mississippi occurred in about .5% of the runoff time.

Four references on sediment graphs found in the literature are the following: Renard and Laursen[20], Bruce et al.[21], Rendon-Herrero[22] and Williams[23]. Of these, Bruce's and Rendon-Herrero's methods require gaged data. Renard and Laursen's and Williams' methods have received limited testing and are not universally applicable to areas other than where they were developed. It would be expected that if sediment graphs could accurately be generated for ungaged watersheds, that they could be useful in improving the trap efficiency of sediment ponds.

This concludes the discussion of the hydrologic tools and terminology generally used in the study of sediment control. With the exception of the discussion of sediment graphs, all material reviewed should be able to be found in any textbook on hydrology. The particular texts used in this review were references 16, 18, 24 and 25.

SEDIMENT

This discussion of sediment will begin with a look at the physical and chemical properties of the sediment. This will be followed by a review of settling theory and the classification of settling. Finally, various factors influencing settling will be reviewed.

The first physical characteristic to be considered is particle size. Sediment can be divided into four general size categories: gravel, sand, silt and clay. A more refined categorization showing particle size in microns and theoretical settling velocities in cm/sec. is shown in

Table 1. Another means by which particles are commonly classified by size is by the way they are suspended in water. As seen in Figure 4, particles in the size range of 1 micron or larger are considered suspended. These particles are kept in suspension by shear forces due to turbulence. Without the effects of turbulence, these particles would settle to the bottom of an Imhoff cone within a 60 minute period under the influence of gravity. When particles are within the range of 1 to 10^{-3} microns, they are referred to as colloidal dispersions and will not settle out within a reasonable amount of time (60 minutes in an Imhoff cone) due to the force of gravity. Particles which make up colloidal dispersions are kept in suspension by their small size, surface electrical charge or chemical combination with the water. There are two kinds of colloidal dispersions: hydrophobic and hydrophilic. Hydrophobic colloids are kept in suspension due to their electric charge while hydrophilic colloids are kept in suspension because of their affinity for water.[26, 27] Particles less than 1 millimicron are considered dissolved solids and occur in true solution in the water.[26]

In the control of erosion and sediment, it is the finer particles which present the greatest problems. Robinson,[28] Director of the USDA Sedimentation Laboratory at Oxford, Miss. in 1971, stated that, ". . . the fine particles are the principal carriers, are more active chemically, and are transported further before deposition. To control the bulk of the sediment problem concerned with pollution requires controlling the amount of clay and colloidal fractions within the sediment."

Related to particle size and of particular interest in determining trap efficiency of sediment ponds is particle size distributions. From the size distribution of particles, the theoretical design settling velocity can be determined for the desired trap efficiency by using Stokes' Law. Often however, the desired trap efficiency will require that particles in the colloidal dispersion range will need to be removed, indicating that in addition to settling, other methods will need to be employed.

It should be noted at this time that suspended particles are of two types, primary and aggregated. Primary particles result when the binding materials of the aggregates are broken down. In other words, aggregates are composed of primary particles held together by some kind of binding material. The specific gravity of the aggregates are generally substantially lower than the primary particles. Care must be exercised when sampling and handling sediment samples used to determine size distributions so as not to break down the aggregates. Many standard methods used to

Table 1. Settling Velocities of Sediment in Water at 15.5° C
(taken from Skelly and Loy[27])

SEDIMENT CLASS		DIAMETER (Microns)	SETTLING VELOCITY (cm/sec)
SAND	Very Coarse	1000 - 2000	15.24 - 27.40
	Coarse	500 - 1000	7.31 - 15.24
	Medium	250 - 500	3.04 - 7.31
	Fine	125 - 250	0.91 - 3.04
	Very Fine	62 - 125	0.30 - 0.91
SILT	Coarse	31 - 62	0.082 - 0.30
	Medium	16 - 31	0.020 - 0.082
	Fine	8 - 16	0.005 - 0.020
	Very Fine	4 - 8	0.0013 - 0.005
CLAY	Coarse	2 - 4	1.6×10^{-4} - 1.3×10^{-3}
	Medium	1 - 2	7.9×10^{-5} - 1.6×10^{-4}
	Fine	0.5 - 1	2.0×10^{-5} - 7.9×10^{-5}
	Very Fine	0.24 - 0.50	4.5×10^{-6} - 2.0×10^{-5}

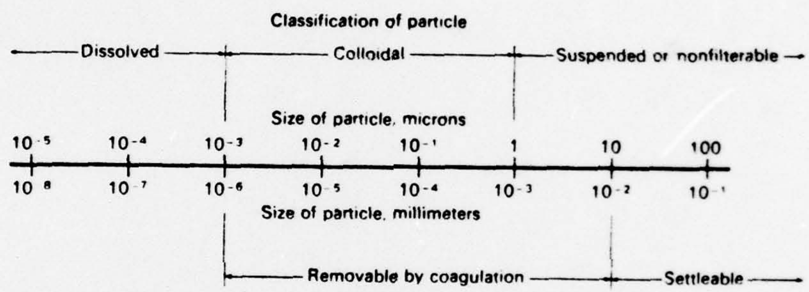


Figure 4. Classification and Size Range of Sediment Particles (taken from Tchobanoglous[26])

determine size distribution employ dispersing agents which will break down the sediment aggregates. No dispersing agents should be used if effective particle-size distributions are to be achieved. Ward et al.[34] in their design manual for the DEPOSITS model outlines specific guidelines to be used in determining size distributions. They go on to state that, "At present, there is very little published information on expected sediment yield from surface mine lands, and even less information on sediment particle size distributions." Young and Onstad[108] reported in 1976 a method by which eroded particle-size distributions could be predicted. Their procedure requires three parameters: particle-size distribution of the matrix soil, organic matter, and water content at -15 bars pore pressure. Although Young and Onstad reported good results using this procedure, it is relatively new and has not as yet received wide usage.

To the author's knowledge, prior to the development of Young and Onstad's prediction method, no satisfactory means of predicting sediment particle-size distributions was available. This was a serious problem in the case of surface mining where it is required by law to construct sediment ponds prior to the disturbance of the land. However, prior to the land disturbance, the size range of sediment particles for which the pond is suppose to be designed was unknown.

A two-fold problem exists here. First, the surface of the disturbed land is generally not the same material as the undisturbed land. This is due to the mining techniques where either the top soil is stripped and stockpiled separately, or else it is overturned in the process of overburden removal. In either case, the surface of the overburden piles is generally subsoil. Secondly, even if the surface material of the overburden piles could be identified ahead of time, the sediment eroded from them will likely have a different composition. Farmer[1] reports in 1976 that, "The properties of sediments eroded from the overburden piles show a degradation in quality as compared with overburden materials. The sediments are more finely textured, have more total salts, contain more sodium, and have a considerably higher pH." Lund et al.[30] found that there is considerable difference in the percent of clay found in sediment than there is in its soil source. Thus, even if the overburden surface material could be identified prior to beginning mining operations, a sieve analysis would not give an accurate idea of the size distribution of the sediment particles which eventually will be eroded away. It should also be noted here that the sediment-size distribution may change throughout a storm event. McHenry and Robinson[29] suggest, ". . . the sediment-size distribution load be defined throughout the hydrograph." Additionally , Willis et al.[31] reported from their study on

Coles Creek and Buffalo River in Mississippi that about 50% of the sediment discharge occurred during about .5% of the runoff time. Thus, if average sediment concentrations and distributions are used in design, the system may be greatly overloaded during peaks.

Another physical characteristic of sediment is shape. Although this property of sediment is rarely mentioned in most articles on the subject of sediment, it has a direct effect on settling velocities. Thus, for the sake of completeness, it will be briefly mentioned here. Sediment is classified into three basic shapes: spherical, rod, and disc. The shape of the particle is important in determing the drag coefficient and subsequently its settling velocity. The drag coefficient can be found for spherical particles, but since the orientation of rod or disc shaped particles is variable, their drag coefficients can not be found with certainty. For Reynolds numbers greater than 1000, the drag coefficients for rod and disc shaped particles vary significantly from that of spherical particles. For Reynolds number less than or equal to 10, the settling velocities of rod and disc shaped particles are 78% and 73% respectively of the settling velocity of an equal volume sperical particle.[32] Under the conditions for which most sediment ponds will be designed, the Reynolds number will be less than 1. Thus, if a spherical shape is assumed, the theoretical settling velocity will be within 73% of the actual settling velocity if disc or rod shaped particles are present.

The last of the physical characteristics of sediment to be discussed is specific gravity. Davis et al.[33] reported in 1978 that the specific gravity of primary particles from upland slopes range from 2.6 to 2.7, while the specific gravity of aggregate particles range from 1.7 to 2. Obviously, the settling velocity of a particle is directly related to its specific gravity (see settling theory below). To handle these variations in specific gravity, Ward et al.[34] recommend that a standard specific gravity value of 2.65 be used in all settling diameter procedures, and that an effective settling diameter be used for the aggregate particles. This value for the specific gravity of sediment is widely accepted throughout the field.

The physical properties of sediment are generally limited to size, shape and specific gravity. Of these, two are assumed to be uniform, shape (spherical) and specific gravity (2.65). Meler[35] in his article about research needs states, "What is needed is more specific characterization of sediment. We have a very detailed classification of soils, but once they erode we refer to them simply as sediment." Meler believes that sediments from different soil types

have significant differences. If these differences can be identified, he suggest that the source of sediment in streams can perhaps be pinpointed. In addition, this may be a useful tool in determining which sediment control measures are most effective. It is the opinion of this author that this might also give some clues as to the sediment size distribution which could be expected once the source material is known.

As stated in the introduction, only those chemical properties of sediment which affect its ability to coagulate will be discussed here. To avoid confusion, definitions of commonly used terms will be presented first.

Coagulation - "The agglomeration of colloidal or finely divided suspended matter, generally caused by the addition of a chemical coagulant."[36]

Flocculate - "to form flocculent masses, as a cloud, a chemical precipitate, etc.; form aggregated or compound masses of particles." (The Random House College Dictionary)

Floc - "a tuftlike mass, as in a chemical precipitate." (The Random House College Dictionary)

Note: flocculate and coagulate are used interchangably.

Hydrophilic colloids - colloids which are stable due to their affinity for water.

Hydrophobic colloids - colloids with no affinity for water; they are stable due to their electrical charge.

The only particles that form colloidal suspensions are those in the size range of from 1 to 10^{-3} microns (see Figure 4). Colloidal suspensions are comprised of clay particles and have such slow settling velocities that coagulants must be added in order to remove the particles within a reasonable length of time. The coagulant causes the small particles to agglomerate or to come together forming larger and heavier particles with faster settling velocities.

Colloids can be of two different types: hydrophilic or hydrophobic. The affinity for water is so great in hydrophilic colloids, that the original aggregates are torn apart, and the fine particles are attracted to the water molecules. In hydrophobic colloids, the particles have an electrical charge of sufficient magnitude that the particles repel each

other and are thus prevented from settling.

Hydrophobic colloids can be removed by neutralizing the electrical charge by the addition of electrolytes. Another method which is effective for both hydrophobic and hydrophilic colloids is to bridge the individual particles with long chain organic polyelectrolytes. The polyelectrolyte actually attaches itself to the surface of the colloidal particles and thus forms large aggregates. A third method is to add a chemical precipitate such as alum, ferrous sulfate, lime, ferric chloride or ferric sulfate. The addition of chemical precipitates will cause the formation of a floc which traps the suspended particles either while it is forming or as it settles. This last method is normally selected for use in wastewater treatment plants for economic reasons. The methods tested for use in sediment ponds for surface mined areas are covered in Chapter IV.

There are four general classifications of settling[27,37]: free, flocculant, zone, and compression settling. Free settling or ideal settling refers to particle settling where there exists no significant interaction between adjacent sediment particles. Each particle settles as an independent particle. Flocculant settling occurs when suspended particles coalesce forming aggregates of increased mass which settle at faster rates than individual particles. Zone settling is a phenomenon where interparticle forces are sufficient to hinder the settling of adjacent particles. The particles remain practically fixed relative to one another and the mass of particles settle together. Compression settling occurs when the particle concentration is so high that a very porous structure is formed. Any further settling is only possible if the structure is compressed.

The two types of settling of interest here are free and flocculant settling. Since flocculant settling has already been briefly mentioned in reference to aggregates, and will be discussed in more detail in Chapter IV, only ideal settling will be discussed further here.

When a particle of sufficient mass/surface area ratio is placed in a fluid, it will be accelerated in the vertical direction by gravity. It will increase in velocity until the force due to gravity is balanced by the drag force. This is known as its terminal or settling velocity. The settling velocity can be expressed mathematically by one of three equations depending on the flow regime determined by the Reynolds number.[37] Where the Reynolds number is expressed as:

$$Re = \frac{\text{settling velocity x diameter of spherical particle}}{\text{kinematic viscosity of the fluid}}$$

For Re < 1, the settling velocity is determined by Stokes' Law:

$$V_s = \frac{g}{18\nu}(S_s - 1)D^2$$

When 1 < Re < 1000, the settling velocity is determined by:

$$V_s = \left[2.32(S_s - 1)D^{1.6}\nu^{-0.6}\right]^{0.714}$$

And when 1000 < Re < 25000, the settling velocity is governed by Newton's Law:

$$V_s = 1.82\left[g(S_s - 1)D\right]^{0.5}$$

Where: V_s = settling velocity, cm/sec.

g = acceleration due to gravity, cm/sec.^{2}

D = diameter of a spherical particle, cm

S_s = specific gravity of the particle

ν = kinematic viscosity of water, cm^2/sec.

In the design of sediment ponds, the settling velocity of the particles of interest will generally be governed by Stokes' Law with some of the larger particles being in the transition region (1 < Re < 1000). Most sediment pond designs are based on ideal settling with settling velocities computed using Stokes' Law. Rarely however do physical phenomenon exactly match theoretical models which are based on simplifying assumptions. Sedimentation in ponds is no exception. It is therefore important to understand where the theory deviates from the observed.

The settling velocity according to Stokes' Law is dependent upon: 1) the diameter of a spherical particle, 2) specific gravity of the particle, 3) the kinematic viscosity of the water. In pond design, a critical settling velocity is selected. The critical settling velocity is the settling velocity of the smallest size particle which is to be removed.

This velocity is calculated using Stokes' Law. It must be remembered however that the theory is based on spherical particles and that rod and disc shaped particles exist in nature as well. As stated earlier, these particles will have a settling velocity of 73-78% of that predicted by Stokes' Law. Thus if critical settling velocities are computed assuming that particles are spherical, error is introduced which may cause the theory to deviate from the observed.

The particles and aggregates which make up the sediment load do not have a uniform specific gracity. As mentioned earlier, an average value of 2.65 is generally used. This however means that the particles with specific gravity less than 2.65 will settle at a velocity less than expected. Thus using an average specific gravity can be another source of error.

The kinematic viscosity of the water varies inversely to its temperature. As can be seen from Stokes' Law, the settling velocity is inversely proportional to the kinematic viscosity. Therefore, the colder the water is, the longer it will take particles to settle. Thus, when temperatures drop below the design temperature, the trap efficiency will be reduced.

It is suspected that water quality may have some effect on the settling behavior of sediment. Obviously if the sediment concentration becomes too great, the type of settling will change from ideal to zone or compression settling. Other water quality measurements such as pH, iron, manganese, etc. will likely affect flocculant settling as will be discussed later. No reference, however, has been found in the literature about the effects of water quality on ideal settling.

Two other factors which will affect the accuracy of Stokes' Law in predicting pond performance is resuspension and short circuiting. Since these two factors are controlled by pond design and are not due to simplifying assumptions of Stokes' Law, they will be discussed in Chapter IV.

Thus in summary, it is the assumptions made about particle shape, specific gravity and water temperatures which are likely to cause the actual settling to deviate from that which is predicted by Stokes' Law.

EROSION

One of the more concise descriptions of the different types of erosion is given by Foster and Meyer.[38] "Sheet

erosion is the removal of a thin relatively uniform layer of soil particles. 'Rill' erosion is erosion in numerous small channels that are small enough to be obliterated by normal tillage; larger upland channels are called gullies. Stream channel erosion occurs by streamflow, and mass erosion is soil movement enmasse." These definitions were selected for use here because of their brevity. For more detail the reader is referred to the original document and/or Sediment Engineering.[39]

The type of erosion of main concern in surface mining is sheet and rill erosion. Sediment ponds will be located as close to the disturbed area as possible and thus channel flow and therefore channel erosion will be minimal. Nevertheless, channel erosion control practices will need to be employed in diversion and interceptor ditches as well as in the channel receiving the pond effluent. On site conservation practices should eliminate any gully or mass erosion.

Erosion is defined as the detachment and transport of soil particles from their original location. Detachment of soil particles occurs in two different ways. Soil particles can be detached by the kinetic energy imparted to the soil mass by the falling raindrops, or they can be detached by the shearing action of the runoff water as it flows over the surface of the soil mass. It should be noted that chemical weathering and freeze-thaw effects are responsible for erosion of rocks. The concern here however is the erosion of soil by rainfall.

The transport of the detached soil particles occurs in two ways also. First, soil particles can be transported by raindrop splash. The second and more prevalent means is the transport of soil by the overland flow of the runoff. The transport of soil particles by flowing water occurs in sheet, rill, gully and channel erosion. The sediment which is transported in streamflow is generally divided into two categories: wash load and bed load. It is impossible to make a complete distinction between the two. However, wash load is considered to be particles carried mostly in suspension. The bed load is defined as ". . . material moving on or near the bed . . ."[39] Thus, part of it may be suspended. The majority of the bed load however is saltated and rolled or slid along the bed.

There are several reasons for the two classifications of sediment load even if the two classifications overlap somewhat. The average sediment particle sizes are different; the average particle size of the wash load are smaller than the average bed load particle size. The mechanics of the transport processes are different, as are the means of measuring the sediment load in each category. Consequently, there

are different concerns in controlling each. Bed load material is coarser and heavier and can easily be trapped by reducing the flow velocity. If it has not already been removed by a check dam or other structure, the bed load will be deposited near the entrance of the pond. Storage becomes a problem since the particles are large and will be completely removed.

Wash load material on the other hand consists of essentially smaller particles, many of which may be in the colloidal range. Removal is more difficult and time consuming, sometimes requiring the use of coagulants and/or filters. Storage is less of a problem due to the smaller particle sizes.

The factors which influence erosion include climate, soil properties, topography, land management and flow properties. Climate affects soil erosion in several ways. Rainfall intensity, duration and frequency are all factors in determining soil erosion. Wischmeir[40] uses the rainfall intensity to determine the kinetic energy available to do the work of detaching soil particles. The intensity, together with the duration of the rainfall, determine for a given soil condition, the rate of infiltration and consequently the amount of runoff. The amount of infiltration is important because it is perhaps the largest source of abstractions and therefore has the potential of significantly reducing the amount of runoff. Infiltration is dependent on storm frequency to the degree that the frequency of rain determines the soils' antecedent conditions. Wet antecedent conditions will reduce infiltration capacity rates and therefore produce higher runoff rates than would be expected for dry antecedent conditions. Jens[41] shows graphically the infiltration capacity reduction for wet antecedent conditions. All of these factors are important in determining the runoff which is responsible for the detachment and transport of soil particles.

Climate also affects the type of vegetative cover that can exist. Vegetative cover in turn reduces erosion by absorbing the rain drop impacts, reducing runoff by means of interception, reducing the runoff velocity and by providing a root structure which helps guard against the formation of rills. Freezing winter weather and snow also affect erosion. During winter months the vegetative cover is generally less dense, however, precipitation amounts during these months are generally less also. When preciptitation does occur in the form of rain, the ground is likely to be frozen which will decrease infiltration and increase runoff. The frozen ground however is generally less susceptible to soil particle detachment due to raindrop impact or overland flow. The most serious erosion problems will occur in the spring when snow melt and spring rains combine for unusually high rates of runoff. This combined with sparse vegetation

and soft thawing soil create ideal conditions for large soil losses.

Erosion rates in the United States have been found to be the highest where the annual effective precipitation is between 10 and 14 inches (25.4 - 35.56 cm). Rainfall below 10 inches does not produce enough runoff to carry away much sediment. When rainfall exceeds 14 inches (35.56 cm) per year, the added rainfall produces a denser vegetation which protects the soil from erosion.[51] From these examples, the role that climate plays in influencing erosion is obvious.

Soil properties will also affect the amount of erosion in several ways. Some soils will support vegetation better than others; the advantage of dense vegetation cover has already been mentioned. The soil type also has a great effect on the infiltration rate; the effect of infiltration has already been mentioned. Finally, some soils are just more susceptible to erosion. There are many factors which determine a soil's erodibility; they include the following: primary particle size distribution, soil structure, iron and aluminum oxides, organic matter, moisture content, wetting-aging, and electro-chemical bonds.[38] The Universal Soil Loss Equation (USLE will be discussed in detail later) contains a soil erodibility factor for which Wischmeier et al.[42] developed a nomograph. The nomograph considers percent silt and very fine sand, percent organic material, soil structure and permeability. Romkens et al.[43] developed a regression equation for erodibility of high clay subsoils which considers the percent of silt, very fine sand, sand, Al_2O_3, Fe_2O_3 and SiO_2. Singer et al.[44] found that soil erodibility was related to the critical tractive force of soil. However, no means of using this to predict soil erodibility have been presented yet.

Topography affects erosion because it governs the manner in which rainfall will runoff. Slope and length are the two important factors of topograph. The steeper the slope, the higher the runoff velocity. Higher runoff velocities 1) decrease infiltration, 2) increase the potential for particle detachment by shear, and 3) increase the sediment carrying capacity of the runoff. Also, the transport of soil particles by raindrop splash will be greater on a hill side than on level ground. This is because the probability of transporting particles by raindeop splash is equal in all directions. Since the raindrop pattern is fairly uniform over an area, the net transport will be near zero for level ground. However, on sloping ground the raindrop splash does not travel as far up hill as it does down hill with the result of a net transport downhill.[18]

The Universal Soil Loss Equation includes a factor for the topography called the length/slope factor, LS. The shape of the slope is also important whether it is convex, concave or complex. The USLE handles these shapes by approximating them with shorter straight line segments. A more detailed discussion on the LS factor will be presented in the section on the USLE.

Land management refers to land use, surface cover, residual land use effects, and structures used to control erosion and sediment. Structures and surface cover will be discussed in detail in Chapter III. Land use and residual land use effects mainly refer to surface conditions. Whether the land use is agricultural, forest, residential, surface mining or whatever, it is essential to know how the surface condition affects raindrop impact, infiltration, runoff and runoff rates. Important also is how the land use may change the soil structure and composition, and possibly even the topography. Surface mining for instance, will significantly change the topography and may well totally change the surface material by overturning it and replacing it with subsoil. Even if the top soil is returned to the surface, chances are that its density is changed and its original cover is missing. Another example of the effect of land use is in agriculture, where tillage acts as a detachment mechanism and will significantly increase erosion susceptibility. Sometimes the management history of the land will have an effect on erosion rates. For instance, cultivated land that had been in meadow 2 or 3 years previously will be less susceptible to erosion than a field which has been continually cultivated. The fine root structures from the plowed under meadows help maintain infiltration and protects against erosive forces.[38]

Flow properties have already been discussed earlier. Briefly, the volume and velocity, particularly the later, will determine the carrying capacity of the water. Also, increases in velocity will increase the soil detachment capability of the flowing water.

The factors which influence erosion have been briefly presented. There is much published literature on this subject and there is a continuing effort to quantify more precisely each of these factor's role in the erosion process. One of the most difficult parts in this effort is to accurately measure erosion rates.

There are several methods to determine erosion or sediment rates. The expression "soil erosion" is used to denote the soil which has been moved from its point of origin. "Sediment yield" is defined as the amount of sediment which leaves a watershed. The sediment yield divided by the soil

erosion is defined as the "delivery ratio."[16] In other words, the delivery ratio is the fraction of the total amount of eroded soil which leaves the watershed prior to its deposition. The goal is to be able to determine sediment yield. Sediment yield is generally measured in tons per unit of time. The unit of time will vary depending on the method used to determine the sediment yield and the reason for determining it.

There are several reasons for predicting sediment yield. One of the first reasons was to determine the storage requirements necessary for flood control structures. For this purpose, sediment yield was desired in ton/year (MT/year).

Another reason for which sediment yield predictions are important is for use in design of erosion and sediment control structures. Not only is it desirable to know how much sediment will be required to be trapped and stored, but equally important, it is desirable to be able to predict the sediment yields for the same watershed after erosion and sediment control methods have been employed in order to determine their effectiveness. For this purpose, the time unit may be quarterly, monthly or even on a storm basis.

With the present enviromental regulations governing water quality, it is desirable to know the sediment concentrations entering the sediment pond. Concentrations are generally measured in milligrams per liter (mg/l) or parts per million (ppm). Thus the sediment yield must be known along with the runoff volume. Sediment concentrations vary with time and runoff rates, but not necessarily in proportion to runoff rates.

Besides the reasons mentioned above, models to predict sediment yield serve another useful purpose. That is, they provide an orderly step by step approach of a very complex process that varies both in time and space. This provides a tidy framework upon which information gaps become readily apparent. Thus an overall picture is provided for researchers of different interest.[135]

There are a multitude of methods for determining or predicting sediment yield. There are almost as many different ways of categorizing them, and there appears to be no consensus as to the best method. Some of the different means of categorizing the predictive methods are listed below:

U.S. Army Corps of Engineers[45] (COE)

a) Methods involving predictive equations
b) Methods involving extrapolation of measured records

Soil Conservation Service[46] (SCS)

a) Gross-erosion and sediment delivery ratio
b) Predictive equations
c) Suspended-sediment load measurements
d) Sediment accumulation measurements

U.S. Environmental Protection Agency[47] (EPA)

a) Empirical
b) Statistical
c) Simulation

Kimberlin and Moldenhauser[48]

a) Statistical equations
b) Methods using time variant interactions of physical process

There is no one method used by all of the federal agencies (Corps of Engineers, Environmental Protection Agency, Bureau of Reclamation, Soil Conservation Service). In fact, none of the agencies limit themselves to any one method. A particular method will be selected based on the specific sediment yield prediction needs, existing data, available time and money. It might be noted however that the method which appears most frequently in the literature, textbooks and regulations is the Universal Soil Loss Equation (USLE). The USLE was first developed for agricultural lands east of the Rockies. However, since its development, much additional data has been gathered for verification of the equation for other land uses throughout the country. It is becoming widely accepted and in a recent USEPA[49] publication, it was acclaimed as ". . . the best index presently avail ble to predict relative soil loss due to sheet and rill erosion." There still exists limitations in its use and more research data is needed in some areas. These will be covered in more detail later.

It is not the purpose here to review all of the different methods available to predict sediment yield. Many of the methods are not applicable for use in the study of sediment control for surface mines.

As mentioned above, there exists a variety of uses for sediment prediction, and the particular use will determine the desirable characteristics of the method to be selected. What are some of the characteristics l ked at when selecting a method? The time factor is one of the most important

factors in selecting an appropriate method or model. Some methods will predict sediment yield on an annual basis. This is ideal when determining the sediment storage capacity for a flood control reservoir but, is not appropriate when concern is focused on water quality. For water quality work, sediment yield is desired at least on a storm by storm basis and preferably on a time interval of say 5 to 15 minutes so that continuous concentrations throughout the storm may be determined. The size of the watershed for which the method was designed is also important. Some methods try to transfer data from one watershed to a similar one. This can be done with some accuracy for larger watersheds, but not so accurately for smaller ones. This is because differences tend to average out over large watersheds and specific local effects are not so apparent. This is not the case for small watersheds.

The source of sediment is another important factor when selecting a predictive method. The source may affect the hydrologic conditions significantly. For instance, urban watersheds will experience more and quicker runoff due to the high percentage of paved areas. The source will also dictate the type of sediment, this is important because of the different ways in which different types of sediment are transported and controlled. Finally, the source may determine the type of erosion to expect. For instance, for surface mined areas sediment ponds will be located as close as possible to the disturbed land. Therefore in most cases, there will be very little channel or stream flow. The majority of erosion will be sheet and rill as opposed to channed, flood plain scour, streambed degradation and valley trenching, etc.

Thus in selecting a predictive model, the predictive needs must be examined. Among the important elements to consider are time, watershed size, and sediment source.[50]

References 45, 46, 47, 48, 51 mention and describe the current sediment yield prediction methods. Not all of these methods are applicable for the sediment problems of surface mining. Furthermore, some have been developed for, and are limited to use in specific geographical locations. The only methods which will be discussed here in any further detail are the Universal Soil Loss Equation (USLE) and the Modified Universal Soil Loss Equation (MUSLE). These two methods have received the most attention in recent literature for predicting sediment yield for surface mined areas. Since the Federal regulations prescribe the use of the USLE, it is likely to continue to receive much attention at least for the next few years.

As mentioned earlier, one of the most universally used

and widely accepted methods of predicting soil loss is the Universal Soil Loss Equation (USLE). Note that this equation actually predicts gross soil erosion and not sediment yield. If there exists frequent opportunity for sediment deposition between the field and the point where sediment yield predictions are desired, a delivery ratio must be determined. The results of the USLE multiplied by the delivery ratio will give the predicted sediment yield.

In 1965, Wischmeier and Smith[52] published their improved version of Musgrave's equation along with proposed procedures and nomographs. This equation which was developed in the late 1950's at the Soil Loss Data Center of the Agricultural Research Service (ARS) at Purdue University has become known as the Universal Soil Loss Equation (USLE). The original equation was based on data collected from 48 locations in 26 states.

The USLE, Equation 1, assumes that erosion is dependent on four factors: 1) rainfall, 2) soil type, 3) topography, and 4) land mangement. The equation is empirical, and the factors, which are interdependent, have been developed in English units. The interdependency of the factors makes the direct conversion of the factors to the metric system impossible. However, reference 40 explains how the whole equation can be converted to the metric system. It should be remembered however, that most tables which give the values for USLE factors were developed for English units.

The simple multiplication of the four factors will yield the gross soil erosion in mass per unit area per unit of time. The normal time unit associated with the R factor is year, while the mass per unit area associated with the K factor is tons per acre. Thus, the gross soil erosion is normally computed in tons/acre/year.

$$A = R \cdot K \cdot LS \cdot CP \qquad \text{EQ. 1}$$

Where:

A - Calculated soil loss, tons/acre
R - Rainfall Factor
K - Soil Erodibility Factor
LS - Length-Slope Factor
CP - Control Practice Factor

The rainfall factor accounts for the interrelationships between the erosive forces of the falling rainfall and the runoff. The two quantities used to determine the rainfall

factor are the average intensity and the maximum 30-minute intensity. Isoerodent maps have been developed to provide average annual erosivity or rainfall factors throughout the United States. Also, tables are available which make it possible to compute the average monthly values based on geographical location. For more detail on the rainfall factor and the factors to follow, the reader is referred to references 16, 40, 42, 52.

The soil erodibility factor, K, takes into account the soil type and its susceptibility to erode. It is the soil loss rate per erosion index unit for a specified soil as measured on a control plot of specified size and slope under specified conditions. A nomograph has been developed for determining the soil erodibility factor for a given soil based on the percent silt, sand, very fine sand, organic material, soil structure and permeability.

The length slope factor, LS, accounts for the topography of the watershed. The LS factor is the expected ratio of the soil loss per unit area for a given slope to the soil loss per unit area having a 9% uniform slope. All other conditions are considered to be equal. Table 2 shows the LS factors for slopes ranging from .2% to 20%, for lengths of 25 to 1000 feet. The references given above also show how concave, convex and complex slopes are handled.

Finally, the control practice factor CP accounts for the effect of land management. Originally two factors were considered, the cropping management factor and the erosion-control factor. Both have been combined and are referred to as the control practice factor. It is defined as the ratio of sediment loss from a field with a given cover and conservation practice to that of a field in continuous fallow. Many tables are available which give the CP factor for a variety of different type covers and conservation practices.

As stated earlier, the USLE has been acclaimed to be the best soil loss index available.[49] It has gained wide acceptance by soil conservationists and has been used in several different disciplines. Although originally developed for use on agricultural land, it has been used for urban areas, construction sites and surface mined areas. When using the USLE, the user should be well aware of its limitations. It was developed to give estimations, not absolute values, for soil erosion for agricultural land. It estimates sheet and rill erosion only, not gully, channel, flood plain, mass, etc.[16] It must be remembered that the USLE does not presently evaluate fluctuations in antecedent surface conditions and storm characteristics. Although it has been used to predict sediment yield for single storms and tables exist

Table 2. Values of LS Factor for Specific Combinations of Slope Length and Steepness (taken from Reference 40)

Percent slope	Slope length (feet)											
	25	50	75	100	150	200	300	400	500	600	800	1,000
0.2	0.060	0.069	0.075	0.080	0.086	0.092	0.099	0.105	0.110	0.114	0.121	0.126
0.5	.073	.083	.090	.096	.104	.110	.119	.126	.132	.137	.145	.152
0.8	.086	.098	.107	.113	.123	.130	.141	.149	.156	.162	.171	.179
2	.133	.163	.185	.201	.227	.248	.280	.305	.326	.344	.376	.402
3	.190	.233	.264	.287	.325	.354	.400	.437	.466	.492	.536	.573
4	.230	.303	.357	.400	.471	.528	.621	.697	.762	.820	.920	1.01
5	.268	.379	.464	.536	.656	.758	.928	1.07	1.20	1.31	1.52	1.69
6	.336	.476	.583	.673	.824	.952	1.17	1.35	1.50	1.65	1.90	2.13
8	.496	.701	.859	.992	1.21	1.41	1.72	1.98	2.22	2.43	2.81	3.14
10	.685	.968	1.19	1.37	1.68	1.94	2.37	2.74	3.06	3.36	3.87	4.33
12	.903	1.28	1.56	1.80	2.21	2.55	3.13	3.61	4.04	4.42	5.11	5.71
14	1.15	1.62	1.99	2.30	2.81	3.25	3.98	4.59	5.13	5.62	6.49	7.26
16	1.42	2.01	2.46	2.84	3.48	4.01	4.92	5.68	6.35	6.95	8.03	8.98
18	1.72	2.43	2.97	3.43	4.21	3.86	5.95	6.87	7.68	8.41	9.71	10.9
20	2.04	2.88	3.53	4.08	5.00	5.77	7.07	8.16	9.12	10.0	11.5	12.9

Note: The dotted lines have been added to show length and slope combinations of test plots from which the data was obtained. All other values have been extrapolated.

for R values for single storms, "The USLE is not recommended for prediction of specific soil loss events."[40] References 53 and 54 will provide the reader with further details of the uses and limitation of the USLE.

Williams[55] in 1975 modified the USLE to eliminate the need for a delivery ratio. In his version, known as the Modified Universal Soil Loss Equation (MUSLE), the rainfall factor R is replaced by a runoff factor. The runoff factors reflect the same basin characteristics as delivery ratios, such as: drainage area, stream slope and watershed shape.[55] MUSLE requires both runoff volume and peak-flow rates, and is expressed as:

$$Y = 11.8\ (Q \times q_p)^{.56} \cdot K \cdot CP \cdot LS \qquad \text{EQ. 2}$$

Where:

Y = the sediment yield from an individual storm in MT
Q = the storm runoff volume in m^3
q_p = the peak runoff rate in m^3/sec.

All other terms are the same as in the USLE. The model was tested om 26 watersheds located in Texas. The results of these tests reported by Brendt[56] indicate that the model can predict fairly accurately the daily, monthly and annual sediment yield.

Williams[55] states that, "Although the runoff factor is a good sediment-yield predictor, more research is needed to insure that the modified equation is applicable to most small watersheds. All available small-watershed data should be analyzed to determine the optimum values of the coefficients in the predictive equation. Also, more work is needed to determine guidelines for selecting erosion-control-practice factors for watersheds."

Chukwuma[109], in 1979, modified Wischmeier's rainfall factor and Williams' runoff factor. Chukwuma's runoff factor, R, is composed of two parts, one for sheet erosion and another for rill erosion. In the development of this modified runoff factor, it is necessary to measure the duration of the runoff hydrograph for which the runoff magnitude is at least 60% of the peak runoff. This in essence allows the R factor to portray more information about the runoff characteristics than merely peak and total runoff. This runoff factor, like Williams', is used in predicting sediment yield for single storm events. Limited tests conducted by Chukwuma indicated his modified version improved the prediction

capabilities of the USLE for single storm events.

MEASUREMENT

It is sometimes desirable or necessary to actually measure the suspended sediment and the bedload of a particular water course. It is recalled that suspended sediment plus bedload equals the total sediment load. Due to the differences in characteristics of suspended and bedload sediment and the differences in the way they are transported, different means of measuring them are required. Attention will be restricted here to methods of measuring suspended sediment for two reasons. First, the erosion of chief concern in surface mining is sheet and rill which produces little bedload material. Secondly, bedload material can be easily trapped, whereas control of the suspended sediment causes the greatest problems in water quality.

There are four reasons for desiring to measure suspended sediment. The first is in order to insure that water quality standards are being met. For example, the Ohio Department of Natural Resources[57] and the Ohio Environmental Protection Agency require the effluent from sediment ponds be sampled twice monthly. Second, measured sediment concentrations are used to calibrate and verify predictive models. Third, suspended sediment measurements have been used to develop rating curves which are used to extend sediment data and to estimate annual rates. They are also used to transfer data from gaged to ungaged watersheds in order to predict sediment yield. And finally, measurement of suspended load allows the effectiveness of various control methods to be determined.

One of the oldest and most widely used means of measuring suspended sediment is to take a water sample and analyze it in the laboratory. The problem arises as to how to obtain a representative water sample. Two general techniques have been used. The first and preferable method is to take a fractional part of the flow as it passes over a weir or spillway, The advantage to these methods is that the samples are generally more representative since they do not disturb the hydraulics of the streamflow since the samples are withdrawn from the flow as it is dropping from a weir or spillway. The disadvantage is that a drop structure providing several feet of fall is required. At least four instruments have been developed to sample stream flow in this method: 1) Splitter samplers, 2) Fractional water-sediment samplers, 3) the Coshocton wheel, and 4) the rotating arm sampler.

Brown[58] describes a series of splitters which progressively

reduce the sample size from 1/600 to 1/6000 to 1/60,000 of the total volume of flow. The first splitter (a Barnes splitter) consists of a sharp edged slot which extends from the crest of the drop structure downstream sufficiently far to continuously collect water samples from the full nappe of the design flow. The slot width of the sampler can vary depending on the size sample desired. The second splitter reduces the sample size by a factor of 10. It consists of a slot in the bottom of the Barnes splitter 1/10 the width of the splitter channel. Similarly, the third splitter reduces the sample by a factor of 10. Brown indicates that estimates of suspended sediment load by use of this method yields results with errors usually less than 18%. A drop structure providing an approximate 4.5 feet (1.37 m) drop is required.

Heinemann and Brown[59] describe the fractional water-sediment sampler. This sampler unlike the splitter mentioned above is hand operated and requires two people. A drop structure providing a 30 cm drop is required. The sampler also has a sharp edged slot which is held at the nappe of the drop. The slot is sufficiently long to collect a full vertical profile at one time. By moving the sampler across the full width of the drop structure, a fully integrated sample is collected. Adapters can be used to further divide the sample if smaller samples are required.

Carter et al.[60] describe the operation of and field testing of the Coshocton wheel. This composite sampler was developed to estimate runoff and soil loss from experimental areas. It requires an apron approach, approach box and flume. The flow from the measuring flume falls upon a circular disk equipped with fins on its surface. The flow hitting the fins causes the disk to rotate on its axis which is inclined slightly from the vertical. The disk has a slot in it which extracts a portion of the flow as it passed under the jet discharged from the flume. The disadvantages of this system is that it requires several feet of drop, is sensitive to asymmetric approach velocities and therefore, requires special approach aprons, boxes and flume, has a maximum flow rate that it can handle, and finally it does not operate correctly for heavy loads of coarse material like sand. Wang et al.[61] describe a modified H-flume for use with the Coshocton wheel. With this modification, sand-sediment concentrations up to 18,600 ppm can be satisfactorily handled. However, the percent of coarse and fine particles collected by the sampler varies with sediment concentrations and flow rates.

Swanson[62] describes the rotating arm sampler. This system is capable of collecting either discrete or composite

samples. It consists basically of a hollow rotating arm with a dipper attached to the end. The dipper and rotating arm scribe a vertical circle as it is driven by an electrical gear reduction motor. The dipper is connected to the rotating arm with a right angle elbow. As the rotating arm scribes the lower part of the vertical circle, the dipper passes under the discharge flume and extracts a sample from the discharge. As the dipper and arm rise, the dipper is gradually inverted and the sample drains through the hollow rotating arm and is collected and stored automatically. The size of the entry slot in the dipper as well as the rotating speed can be varied to obtain the desired sample size. This system requires several feet of drop, a measuring flume, and an electrical power source. Swanson[62] noted no significant operational problems and reports excellent results when the system was used at a research site at Gretna, Nebraska in 1969. Recently however, Bonta[107] has reported that variations in the percent of sampled flow have been observed when the flow rate increases. No explanation for this phenomena has been found.

In the other method of obtaining samples, the samples are withdrawn directly from the stream. The advantage is that no drop structure is required. The disadvantage is that it is difficult to obtain a representative sample from across the entire cross section and that it is difficult not to disturb the flow when taking the sample. Numerous devices have been developed to take samples in this manner. There are basically two means of classifying these samplers. They are presented in outline form below:

Classification I

i) Integrating samplers
   a) point-integrating
   b) depth-integrating

ii) Instantaneous samplers

iii) Pumping samplers

iv) Special samplers

Classification II (From Reference 36)

i) Intake is oriented parallel to stream flow
   a) sample container and intake nozzle mounted as one integrated unit with short conduit connecting the two
   b) sample container and intake as one integral unit

c) sample container separated from intake by several feet of conduit

ii) Intake is oriented perpendicular to stream flow
   a) sample container and intake nozzle mounted as one integrated unit with short conduit connecting the two
   b) sample container separated from intake by several feet of conduit
   c) sample container without nozzle or conduit

No mention of instantaneous samplers was discovered in the U.S. literature reviewed herein; however, a Polish publication[63] describes three such devices. These instruments have various capacities ranging from 1-5 liters. As is implied by their name, these samplers are instantly filled as opposed to the slowly filled integrating samplers. The main disadvantage of instantaneous samplers is that they can not account for ". . . the pulsation of a stream's turbidity during sampling . . ."[63] The three instantaneous samplers described in the Polish publication are the following: P.I.H. made in Poland, Zhukovskii type made in Russia, and the Collet type used in France.

Integrating samplers, as can be seen from the outline, can be either point-integrating or depth integrating. The depth integrating sampler is used to continuously obtain samples throughout the vertical profile as the sampler is lowered and than raised through the stream depth. The Inter-Agency Sediment Project[64] developed three depth integrating samplers ranging in weight from 4.5 lbs. (2.04 kg) to 62 lbs. (28.12 kg). Reference 36 lists and describes no less than 10 depth integrating samplers. The U.S. designed integrating samplers (both point and depth) are designed to sample isokinetically, that is, the sample water does not accelerate as it leaves the stream and enters the sampler. The depth integrating samplers have nozzle sizes ranging from 3.2 mm to 6.4 mm located from .3 ft. (9.1 cm) to .4 ft. (12.19 cm) above the bottom of the sampler. Although the nozzles have no valves, there is an exhaust tube which allows air to escape as the sampler fills with water.

Point integrating samplers are considered more versatile than the depth integrating.[36] They can collect samples over a period of time at any place within the stream cross section, except within a few inches of the bottom. They can also be used as a depth integrating sampler. The point integrating sampler has an electrically operated valve which usually has three positions: closed, open, and one which allows equalization of the pressure on the inside with the

hydrostatic pressure. These models also include exhaust ports which allow air to escape while the sample fills with water. Reference 36 lists and describes five different point integrating models.

Pumping samplers are intended for use at permanent or semi-permanent installations. They are operated by a timer which can be set to obtain samples at any desired frequency. Samples are collected and stored in liter or half liter bottles. The samples are not isokinetically collected and the intake is usually oriented perpendicular to the flow. This gives fairly accurate results for clay and fine silt particles, but not for coarser particles. The sampler can be activated by a manual switch, but is more commonly activated by an automatic switch when the stream reaches a predetermined stage. These types of samplers are ideal for sampling during storm events particularly in isolated areas. Their disadvantage is that they do not sample isokinetically, and are therefore, not reliable for sampling coarser particles. Reference 36 describes two pumping samplers.

Finally, there are a few samplers classified as special samplers. The first is a single stage sampler described in both references 36 and 64. The advantages are that they can be installed for a predetermined stage before the storm, and do not need to be attended. They are also inexpensive. The disadvantages are that samples will be collected at or near the surface and usually close to shore. Sampling will probably not be isokinetic, and flow may circulate through the sample after the original sample is collected. Finally, the intake nozzle may become clogged with debris or insects. Another sampler which is described in reference 36 is a flow through sampler which can be closed off by a spring mechanism at any predetermined stage.

The second means of sampler classification listed above is self explanatory. The integrating and instantaneous samplers have their intakes oriented parallel to the flow. The pumping samplers generally have their intakes oriented perpendicular to the flow to avoid being clogged with debris.

Other methods have been and are being explored to determine sediment concentrations directly without the need of obtaining a sample for laboratory analysis. These methods include electronic sensing methods, turbidity methods, ultrasonic and nuclear methods. Of all methods, the turbidity meters show the most promise at present. Turbidity meters operate on the principle of measuring the light which is reflected as a beam of light is passed through the water. The measure of reflected light is related to the amount of sediment present to reflect the light. Early problems with this method involved the interference caused by algae growth on

the lenses through which the light beam was sent and received. Recent models are self correcting for this growth. Particle size distribution can not be obtained using this method, nor can this method distinguish between organic and inorganic sediment. For further information on any of the above mentioned methods not requiring water samples, the reader is referred to references 36, 64, and 65.

Several problems, some of which have already been mentioned, exist with the present means of measuring sediment concentrations. First, collecting and analyzing samples is both expensive and time consuming. Secondly, the distinction between suspended and bedload sediment is not clear when making measurements close to the stream bottom. The third and most important problem is that of obtaining a representative sample. It must be remembered that sediment concentrations vary spatially and temporally. The spatial variation is observed both in depth and in width. Concentrations will vary in time throughout the duration of the runoff event. Local variations due to pulsations are also observered.

The Coshocton wheel, the rotating arm sampler, and the fractional water-sediment sampler will all provide integrated samples in time and space. However, this will only give an average concentration for use in determining total sediment lost during the event. It is possible, as mentioned earlier, to obtain discrete samples with the rotating arm sampler. The pumping samplers store each sample separately such that the concentrations at different times can be found, but these samples are collected at only one point at one depth. Additionally, in the use of all methods, care must be exercised so as not to disturb the stream flow and interrupt the flow patterns when obtaining samples.

In a research report published by the EPA[66], the point-integrating automatic pumping samplers were found to be of limited value. The samples collected by the pumping samplers when compared to those simultaneously obtained using depth integrating samplers showed absolutely no correlation. The report stated that, "data collected by the automatic equipment is speculative at best."

It should also be noted that once a sample is obtained, care must be exercised in handling, transporting and analyzing the sample such that the aggregates are not broken down.

No ideal method for determining sediment concentrations are presently available. The methods available have been briefly presented here along with their disadvantages. In selecting a method, the requirements and circumstances of the particular case must be reviewed. Additionally, the operator must be aware of and of and understand the limitations of the selected method.

CHAPTER III

EROSION/SEDIMENT CONTROL

INTRODUCTION

This chapter summarizes the "State of the Art" of sediment control for land disturbed by surface mining. One method of sediment control omitted in entirety is sediment ponds which will be discussed in detail in Chapter IV.

The objective of erosion and sediment control for surface mined areas is to protect the receiving waterways from being polluted by soil particles, referred to as sediment. Two approaches are generally employed to achieve this objective. The first is to prevent the soil particles from being eroded in the first place. This is called erosion control, and is sometimes referred to as the first line of defense. No practical erosion control method is 100% effective and thus it is inevitable that some erosion will occur. Thus the second approach is to cause the sediment which has already been eroded to be deposited before the runoff water reaches the natural waterways. This is called sediment control, and is sometimes referred to as the second line of defense.

The problems of erosion and sediment control have been studied in the agricultural and construction fields for many years before it received wide notice in the mining industry. Thus, many if not all of the methods which will be discussed here were originally developed to solve problems in the agricultural or construction fields. Although developed for use elsewhere, these methods can and are being used to solve the same problems in the mining industry.

For the most effective results, control plans must continually be considered as a whole. No one method is likely to achieve the desired results. In fact, most cases will require one or more techniques from each of the two approaches. Needless to say, comprehensive planning is of no less importance in erosion and sediment control than it is in any engineering project. Grim and Hill[68] state that,"One of the primary rules for good erosion and sediment control is that all earth moving activities be planned in such a manner that the minimum amount of disturbed area will be exposed for the minimum amount of time." Curtis[67] in 1974 determined from his study of surface mined land that the greatest erosion occurs

during the first six months after mining. This indicates the importance of a control plan prior to disturbing the land and for its timely execution.

EROSION CONTROL

The methods for erosion control will be reviewed first, followed by methods for sediment control. It should be noted that some methods can be viewed as either an erosion control or a sediment control method or perhaps as a hybrid control. No effort will be made here to delineate between the two since both are approaches of obtaining the desired end result. The only reason for the distinction at all is for discussion purposes.

The specific methods of erosion control will be reviewed by the erosion process which they tend to counteract. As will be remembered from Chapter II, there are two processes in erosion: 1) detachment and, 2) transport. Those methods designed to counteract detachment will be reviewed first.

Detachment occurs either from the kinetic energy imparted due to raindrop impact or from shearing action due to flowing water. Erosion control methods aimed at reducing detachment caused by raindrop impact can do either one of two things: 1) protect or shield the soil by using vegetation or mulches to absorb the kinetic energy, or 2) strengthen or stabilize the soil such that the kinetic energy of the raindrops is not sufficient enough to detach particles.

Mills and Clar[69] state that vegetation is one of the most important means of controlling erosion on surface mined land. However, while a good vegetative cover is being established on newly disturbed land, action must be taken to provide initial protection for the soil as well as the recently planted vegetation. This protection has been successfully provided by mulches, mulch blankets, excelsior blankets, jute netting and other such products.

In addition to providing protection from the erosive forces of rain, mulches also provide a ". . . better environment for germination and plant development by conserving soil moisture, moderating soil temperature, and in the case of organic mulches, providing nutrients to the soil."[69] This last advantage mentioned makes the use of organic mulches more desirable than inorganic mulches. Organic mulches include: straw, hay, woodchips, wood fiber, bark, bagasse, and manure. Inorganic mulches include: plastic sheets, gravel, stone,

chemical mulches, fiberglass and building blocks.

Excelsior blankets, jute netting and mulch blankets as well as several inorganic blankets commercially available are also used as mulches. Netting is also available not as a mulch, but to protect loose mulch from being washed or blown away. Besides netting, crimping and tacking are also methods used to secure loose mulches in place. The best type of mulch and the best employment technique will depend on such site specific factors as climate, slope, soil type, type of vegetation to be seeded, and availablity of materials. For details on types of mulches, methods of application, methods of securing, effectiveness, and costs, the reader is referred to references 49, 69, 70, 71, 72. In addition, the effectiveness of some of these mulches are given in terms of cover and management factors in reference 40 for use in the USLE.

Much research has been done in determining the best type of vegetative cover to use. An EPA handbook on erosion and sediment control[69] explains that grasses and legumes are best suited for early stages of soil stablization, and that scrubs and trees are best used in intermediate and late stages to provide protective canopies and surface organic material from leaf cover. Again, in selecting the type of vegetation to use, many factors are involved such as: germination time, growth habits (ie. annual, biennial, perennial, long-lived, short-lived, etc.), climate and drainage suitabilities, pH tolerance range, flood tolerance, shade tolerance, slope ranges, soil and fertilizer requirements and maintenance requirements. For tables listing different species and their characteristics, the reader is referred to references 49, 69, 70, 71, 72. Much work is presently being conducted in the agricultural field to devise better methods to establish vegetative covers quicker on land disturbed by surface mining. Howard et al.[73] have done research with plant growth in both topsoil and overburden from active mines. They have experimented with N and/or P fertilizers as well as sewage sludge and manure. The data from their research is hoped to be of future value in reclamation and revegetation of surface mined lands. Schuman and Taylor[74] have shown the benefits of mixing subsoils or spoil with the topsoil to obtain suitable soil conditions for revegetation. Ruffner[76] reports on the research conducted by the SCS to identify plants which are best suited for erosion control on disturbed land no longer suitable for its native vegetation. While Konya[75] describes the Hungarian method known as the Biological Reactivation Process (BRP) which requires no special stripping, handling, mixing or replacement of the top soil. In this method, trenches are dug to catch and hold all runoff so that it has time to completely infiltrate into the disturbed land. In addition, the soil

is prepared with fossil organic matters and combinations of nitrogen, phosphate, and potassium, with micro-elements, and micro-organisms. Excellent results using this method in Hungary, Czechoslovakia, Libya and Russia have been reported.[75] Suffice it to say, that much research is underway in finding the best type of vegetation and the best method of soil preparation, and seeding and fertilizing techniques in order to provide maximum erosion protection. No attempt was made to obtain an exhaustive list of references on this subject. The list of 5 references given above fairly well covers the established methods and species. The latter four references, briefly described above, are only a sampling of the type of research being conducted and reported periodically in this active research field.

In the field of chemical soil stabilizers, there is also a wide variety of products available. They are referred to as chemical binders, mulches, or tacks and are usually a latex emulsion, plastic film, resin-in-water emulsion or similar product. As indicated by their different names, these chemical binders can serve three different purposes.[49] First, they can be used as a temporary soil stabilizer for areas waiting final grading or the proper season for seeding. In this use, the binder penetrates the soil and binds the particles into a cohesive mass. Second, they can be sprayed onto a seeded area and act similar to mulches. The water and air movement into the soil is not blocked, and vegetative growth is not hampered, but the soil and seeds are protected against the erosive forces. Third, they can be used to bind organic or synthetic mulches to prevent them from being washed or blown away.

The "Erosion and Sediment Control Handbook"[70] prepared by the Department of Conservation of the State of California, lists several disadvantages of chemical mulches. The chemical mulches are said to form a crust which reduces porosity and inhibits vegetative growth. The crust can be damaged by animals or human traffic as well as by frost heave. The handbook illistrates only two uses: 1) as a binder for wood fiber mulches and, 2) as a temporary means of controlling wind erosion. Twelve different chemical products are listed in its tables.

The other three references: 49, 69, 71 found on this subject, do not indicate the disadvantages listed in the California handbook. In fact, many of the products mentioned in these 3 references claim to maintain air and water movement in the soil, or reduce evaporation losses and in general aid rather than hinder vegetative growth. Reference 69 lists 14 chemical products with their intended uses, application rate, description and manufacturers information. Reference 71 describes 8 chemical products with the same type of information.

Another technique used to aid in the development of a vegetative cover is to roughen, scarify, step, bench, serrate or track the denude slopes. These methods differ only in the type of equipment used. Each method tends to increase infiltration and at the same time provides small cracks or crevices in which seeds can become lodged and thus prevented from being washed or blown away before having a chance to take root. For a description of these different methods, see references 70, 71, 77.

Control measures aimed at counteracting detachment by shearing action due to flowing water will now be reviewed. Detachment by flowing water occurs both in sheet or interrill erosion as well as in rill and channel erosion. Control methods for these different types of erosion will be looked at separately.

First, the methods aimed at controlling sheet erosion will be reviewed. The initial methods to be looked at are those which are designed to prevent runoff from other areas from passing over the disturbed land. Besides reducing the total volume of water which would be available to cause particle detachment, these methods also reduce the volume of water which is required by Federal law to be passed through a sediment pond. (see para 816.42 (a)(1) and (a)(4) of ref. 14) Specifically, the methods referred to here are interceptor dikes and diversion ditches. The definitions of each of these methods vary somewhat depending on the reference. However, the concept of either of these methods is to prevent rainfall runoff from passing over highly erodible land. This is achieved by blocking or intercepting the runoff by dikes or ditches or a combination of both and routing it to a natural waterway or stable area in which erosion is not likely to be a problem. References showing diagrams, and recommended design are 16, 49, 69, 70, 71, 72. The use of interceptor dikes and diversion ditches does not completely eliminate overland flow on disturbed land area. Rainfall which falls directly on the disturbed land can, and in most cases will, contribute to overland flow. Diversion dikes merely prevent runoff from other areas from passing over the disturbed land of interest.

Since it is impossible to completely eliminate runoff over the disturbed land, it will be desirable to employ methods which will reduce the runoff's effect. To do this, two approaches are possible: 1) reduce the runoff volume, and/or 2) reduce its velocity. Vegetative covers which have already been mentioned, achieve both of these. Vegetation will reduce the velocity of the runoff and will also increase infiltration and thereby reduce the runoff volume. Kao and Barfield[78] have studied the hydraulic properties of flow through

artificial dense vegetation. They report that flow at non-submerged depths among randomly patterned vegetation blades result in dominate drag resistance forces which hinder the flow. By reducing the velocity, two beneficial effects are achieved: 1) the particle detachment capability due to shearing action is reduced due to a reduction in shear, and 2) the runoff is allowed more time for infiltration. Besides allowing more time for infiltration, the vegetative cover aids infiltration in two other ways. First, its root system increases soil permissibility[69] and second, the vegetation protects the surface against sealing caused by raindrop impact.[79]

One of the most significant factors in erosion is the slope of the land. The fact that slope itself is a factor in the USLE attests to its significance. By examining the values for the LS factors in Table 2, the sensitivity of erosion to the slope is apparent. Since the slope determines the velocity of the runoff, it will also affect the infiltration rate which is dependent in part on the velocity. The slope therefore affects both the runoff volume as well as its velocity. Hill[12] indicates that an increase in slope of from 10% to 40% will double the runoff velocity. He reccommends that steep slopes be avoided where possible with a maximum allowable slope of 33%. Farmer and Richardson[80] studied infiltration rates and erosion of bare overburden piles in surface mines in southeastern Montana. They concluded that ". . . steep, tall, dragline overburden piles should be graded and revegetated as quickly as the mining operation will allow." Thus the second method to reduce the effects of surface runoff is simply to reduce the slopes where possible as soon as possible.

Closely related to slope is the length of the slope section. As can be seen from Table 5, the LS factor is proportional to the length. An increase in the slope's length increases the sediment yield. Diversion ditches can be used to cut long drainage areas into several shorter ones. This will effectively reduce the length and has proven effective in reducing erosion. The runoff from the diversion ditches can be directed to stable slopes or funneled into protective chutes or flumes to be transported safely off the slope. The effectiveness of these diversion ditches has been quantified for use in the USLE. See Reference 16 for control factors for use in the USLE for diversion ditches.

A somewhat similar technique, explained in detail by Noble[81] is referred to as contour trenching. This method is similar in that it involves trenches or ditches which run perpendicular to the grade. It differs in purpose from diversion ditches in that it holds the runoff on the slope so

that it has sufficient time to completely infiltrate. Thus zero runoff is expected from the slope. Contour trenches will normally be found much closer together than diversion ditches. Also, check dams or baffles will be constructed across the trenches at intervals of about 35 feet. Again, the purpose is not to safely route the runoff off the slope but to cause it to infiltrate in totality.

Another method known as impoundment terraces has been shown by Alberto et al.[82] to be extremely effective in reducing runoff and soil loss. It differs from contour trenching in that the water is held on terraces instead of in trenches, and the water is drained through stand-pipes to underground drains instead of infiltrating through the soil. As such, the terraces act as sediment ponds which will be discussed in detail in Chapter IV. The reader interested in impoundment terraces is referred to an article by Laflen et al.[83] titled, "Sedimentation Modeling of Impoundment Terraces." Due to expense, this method is more applicable to agricultural lands than to surface mined areas.

A structure designed to guard against sheet erosion becoming rill and gully erosion due to concentrated overland flow is known as a level spreader. Level spreaders are defined by the EPA [49] as, ". . . outlets constructed at zero grade across a slope where concentrated runoff may be spread at nonerosive velocities, in the form of sheet flow, over undisturbed areas stabilized by existing vegetation." The concept is to reduce the erosive power of the runoff by reducing its velocity.

Thus far, techniques designed to protect against particle detachment in interrill erosion have been reviewed. Now attention will be directed toward rill and channel erosion. In these types of erosion, detachment by raindrop impact is of no concern since the raindrop hits the water surface and not the erodible surfaces. Only detachment due to the shearing action of the flowing water is applicable.

Rills occur in sheet erosion when the runoff becomes concentrated over a particular path. The flowing water erodes a small path making it capable of carrying more runoff and having an increased gradient. Gradually more and more water flows through it at increasing velocities. Erosion increases and the rill grows in size and eventually becomes a gully. To avoid the formation of rills, a good vegetative cover is necessary and concentrated flows must be avoided. One method to do this is by using level spreaders as mentioned above. Sometimes however, rill erosion will occur in ditches or swales designed to carry concentrated flows. In these cases "erosion checks" may be employed. Erosion checks are a porous mat-like material that are placed vertically in

a trench that runs across the width of the ditch or swale. The trench is back filled and the porous material is cut flush with the surface. This membrane allows the passage of subsurface water, but holds soil particles in place; thus preventing the formation of rills. Erosion checks can also be used on critical slopes. The reader is referred to references 49, 70, 71 for construction specifications and cost estimates.

Channels, unlike rills and gullies, are sometimes man-made. Whether they occur in nature or are constructed by man, they serve a purpose of transporting large volumes of water. The objective then is to protect the channel bed and banks from being eroded. Again there are two approaches: 1) reduce the erosive powers by reducing the velocity, and/or 2) protect the channel by lining it.

Velocities in channels can be reduced by decreasing the hydraulic gradient which is accomplished by emplacing grade control structures called check dams across the channel. For design criteria see references 49, 69, 70, 71, 72.

Velocities can also be reduced by dissipating energy by placing obstructions or baffles in the channel. Also, rough channel linings such as vegetation and riprap, besides shielding the channel, will retard flow and decrease velocities. There are many materials which have been used to line channels. They vary from mats made of old rubber tires to gabions to sophisticated and expensive concrete linings. Further detail into the many aspects and factors concerning channel lining will not be presented here. Normally the largest channel flow to be encountered in surface mining will be diversion ditches which will normally have vegetative linings. For the interested reader, further information about channel lining can be obtained from references 49, 70, 71, 72.

Another concern is to be able to drain collected runoff safely down the face of a slope. This is done with concrete or riprap lined chutes or flumes, flexible downdrains, or sectional downdrains. Illustrations for each of these can be found in references 49, 69, 70, 71, 72.

Thus far control measures have been discussed as means to counteract the detachment process of erosion. As will be remembered from Chapter II, the other process of erosion is transport. If more particles are detached than can be transported, then the sediment yield will be governed by the transport process. If, on the other hand, there exists a larger capacity for transporting particles than there is for detaching them, the sediment yield will be governed by the detachment process. It is therefore important to know how to con-

trol both the detachment and the transport processes of erosion.

The methods to control the transport process are the same as many of the methods available to control the detachment process. The transport process, similar to the detachment process can be subdivided into two types: 1) transport by raindrop splash, and 2) transport by rainfall runoff. The most significant type, or one responsible for transporting most of the sediment is the second.

Transport by raindrop splash was discussed in the Erosion section of Chapter II. It was mentioned there that raindrop splash as a transport process only occurs on slopes. The steeper the slope, the greater the net transport in the down slope direction. Figure 5 is helpful in visualizing this phenomenon. To control this process, the steepness of the slope needs to be reduced. This control measure, it will be remembered, was also used to reduce overland flow velocities both to reduce its erosive effect and to increase infiltration and thereby reducing the runoff volume.

Mills and Clar[84] talk about flow characteristics in their paper on erosion and sediment control for surface mines. They state, "As velocity and turbulence increase, the water is able to transport more sediment. Conversely, as velocity and turbulence decrease, the water has less potential for transporting sediment and deposition of soil particles occurs." This is then the basis for controlling the transport process due to runoff. Runoff velocities must be prevented from becoming sufficiently large to be able to pick up and carry large quantities of sediment. In addition, runoff already carrying sediment must be slowed down in order that its sediment load be deposited. Technically, methods to prevent high velocities are erosion control while the methods to reduce velocity to cause depostion should be considered sediment control. The methods mentioned above that reduce runoff volume by diversion or infiltration, or reduce velocities by reduction of hydraulic gradients or dissipation of energy will serve also to control the transport process. No separate methods are available solely for the control of the transport process.

This concludes the discussion of erosion control. It must be kept in mind that even if the best erosion control plan is used, it is almost certain that some erosion will take place. In many cases, the best erosion plan will not be used due to time, cost, convenience or some other factor. In these cases, considerable erosion is likely to occur. In either case when the erosion occurs at sufficient rates such that water quality standards are not met a "second line of

defense" is required. This is known as sediment control and refers to handling or controlling sediment which has already been eroded.

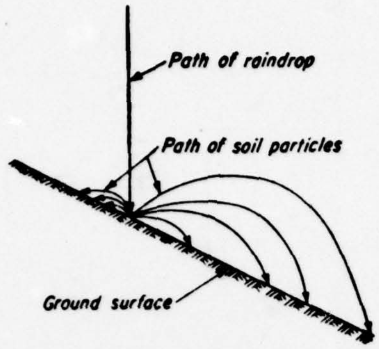


Figure 5. Downhill Transport of Soil Particles by Splash (taken from Linsley et al.[18])

SEDIMENT CONTROL

Sediment control involves either settling or filtering the sediment. Settling is normally done on a large scale such as in sediment ponds which will be discussed in detail in the next chapter. However, the settling phenomenon is also employed on a smaller scale in sediment traps. Check dams act as sediment traps and remove the larger sediment particles, although this is not always their primary purpose. Other types of sediment traps include: sandbag or straw bale barriers, log and pole structures and small excavated pits. The principles involved are the same for each type, namely the structure reduces the velocity and turbulence allowing particles to settle prior to the flow passing over or through the structure. The retention time is short and therefore only the large particles are trapped. Sediment traps are sometimes used at the entrance of sediment ponds to trap the larger particles before they reach the pond and thereby increase the life of the pond or reduce the frequency of clean outs. For more information on the use, construction and cost of sediment traps, the reader is referred to references 27, 49, 69, 70, 71, 72.

Filtering can be used either for pond influent or pond effluent. Filtering can also be employed elsewhere besides in conjunction with sediment ponds. Two such examples are filter berms and filter inlets. Filter berms are temporary berms of crushed rock or gravel placed across a graded right-

of-way to retain runoff while allowing traffic to proceed along the right-of-way. Filter berms can be effectively used on haul roads. For more details on cost and construction, the reader is referred to references 49, 70, 71.

Filter inlets usually consist of straw bales placed around storm sewer inlets around construction sites. These are not particularly applicable to surface mining operations.

Filters used in conjunction with sediment ponds include straw bales, silt fences and vegetative filters. The straw bales and silt fences are normally used at the pond inlet to remove larger particles. For more details see reference 27. Grass filters, when employed, are normally used as a final polish for pond effluent.

Much research is being done with vegetation for use as filters in sediment control. The principle behind its use is that the grass blades hinder the flow due to the increase in drag resistance. As the velocity is reduced, sediment is deposited. One of the most pertinent problems with grass filters is to find a grass which can survive inundation. Kao et al.[89] suggests a possible solution to this problem would be to ". . . alternate patterns of open area with vegetated area . . . Preliminary tests show this may well be a solution to the inundation problems." Some of the most recent research in this area has been done by Barfield and Kao at the University of Kentucky. The interested reader is referred to their publications referenced 85, 86, 87, 88, 89. For guidelines on the application of vegetation as a filter, see references 27 and 70.

CHAPTER IV

DESIGN OF SEDIMENTATION PONDS

INTRODUCTION

This chapter will review in detail the "State of the Art" of the design criteria for sediment ponds for surface mined areas. The different types of ponds will be presented first. This will be followed by a discussion of the operating and close down procedures along with frequently experienced problems. Finally, each of the design considerations will be reviewed separately.

The use of sediment basins to remove solid particles from water is not a new technique. The study of settling to remove sediment from water can be traced as far back as 1904 when Hazen[90] published his article, "On Sedimentation." Since that time, sediment basins have been used as one of the first processes in water and sewage treatment plants. Sediment ponds have also been used extensively on farm lands and in irrigation systems. The coal industry has used sediment ponds called slurry ponds to remove the fine refuse, which results from the washing and processing of coal, prior to discharging or recycling the water. And most recently, the construction industry has employed sediment ponds to control sediment which is eroded from construction sites. Many of the techniques and design criteria to be presented below are a result in part or whole from the long experience in the settling process by the disciplines mentioned above. Although each discipline has requirements and conditions unique to its own interest, there are similarities about the sediment process applicable to each. Thus experience gained in one discipline should be used for the benefit of all when possible.

TYPES OF PONDS

In the EPA publication, Environmental Protection In Surface Mining of Coal,[68] a distinction is made between primary and secondary ponds. Primary ponds are larger and are constructed for the purpose of removing sediment by settling. These are the subject matter of this chapter. Secondary ponds

are of a smaller size usually resulting from the construction of check dams or log and pole structures as mentioned in Chapter III. The purpose of constructing secondary sediment ponds is to trap the larger particles prior to their entering the primary sediment pond. This will save the sediment storage space of the primary pond and prolong its life. The large sediment particles trapped in the secondary pond can more easily and economically be removed there then from the large primary pond.

Skelly and Loy[27] categorize sediment ponds by the type of construction:

1) excavated,

2) sediment dam, excavated,

3) embankment dam.

The EPA distinguishes another type which they refer to as a "leaky dam."[68]

Excavated sediment ponds are constructed by digging a pit or sump with a backhoe or dozer. There are no designed inlet or outlet structures and thus construction is easy and inexpensive. These ponds are limited to small drainage areas or relatively flat areas.

The sediment dam, excavated type sediment pond as its name implies has a constructed embankment to increase the capacity of the excavation. The outlet consists of a channel through the embankment.

The embankment dam sediment pond differs from the sediment dam, excavated type in that its principal spillway consists of a pipe and riser barrel and it has an emergency spillway which is excavated in the natural ground. (ie. not in the fill embankment) This type of pond has the largest storage capacity of the three mentioned.

The leaky dam sediment pond is so named due to the rock-french-drain-type embankment structure which temporarily stops the runoff water. The pond empties as water trickles through the embankment. "It has been used very successfully on small watersheds of less than 150 acres (60 hectares) and on larger areas in combination with earth embankment to catch initial sediment loads."[68]

Sediment ponds may also be classified by whether they are located on or off streams. For off-stream sediment ponds, the runoff from the disturbed area is routed through a

sediment pond prior to reaching the stream. For on-stream sediment ponds, the whole stream passes through the sediment pond which is built across the existing stream. On-stream sediment ponds have base flows where off-stream ponds do not. Generally off-stream ponds are preferable due to ease in clean out and close down procedures. These will be discussed in more detail in the next section of this chapter.

In a report published by Hittman Associates, Inc.[37] for the EPA, it is recommended that off-stream or off-drainage ponds be constructed whenever possible. It should be noted however, that the off-stream ponds reviewed for that report were built such that the runoff did not flow directly into the pond. The runoff first flowed into a pit area from where it was then pumped into the sediment pond. The pit area acted as an initial settling pond, and since the influent was pumped into the primary pond, its rate could be controlled and kept fairly constant. Both of these factors no doubt were partly responsible for the higher effluent quality observed from these off-channel ponds. All off-channel ponds reported in the literature do not have this advantage. Most receive runoff water directly from the disturbed area and therefore flow rates are not steady.

Finally sediment ponds can be divided into one of two groups: 1) permanent pool ponds, or 2) dry ponds.

Permanent pool ponds are those which will maintain a certain level of water at all times. These can be either on or off-channel ponds. On-channel ponds will always have some water, and therefore will be permanent pool ponds. Off-channel ponds can be either permanent pool or dry ponds depending on their outlet design. Generally, permanent pool ponds are preferred since they provide a longer detention time and problems of resuspension are not as great.

FREQUENTLY ENCOUNTERED PROBLEMS/OPERATING PROCEDURES

The frequently encountered problems and cleaning and closedown procedures will be covered now since a knowledge of them will be useful when discussing design criteria and considerations later.

One of the most common problems which occurs in sediment ponds is short circuiting. Short circuiting occurs when the water flowing through the pond takes a "short cut" as it travels from the inlet to the outlet and by-passes a substantial volume of pond storage space. Dead spaces of stagnant water are thus created which are by-passed by the

water flowing through the pond. Where short circuiting is severe, large areas of dead space are created which are virtually useless in terms of improving water quality. Short circuiting reduces detention time since the travel distance between the inlet and outlet has been reduced. Ideally, a pond should operate under conditions known as plug flow. That is where the first water (or plug of water) to enter the pond would be the first water (or plug of water) to leave the pond. In this manner, longer average detention times would be experienced by all the water passing through the pond, and no section of water would become permanently trapped in the pond. Plug flow is an ideal condition which never occurs in practice. Sometimes the first water in from a new runoff event will mix with the permanent pool water instead of forcing it out. Other times the two water bodies may not mix at all due to density differences and the newly arriving water will by-pass or skim over the permanent pool and be the first discharged. In this case, the detention time is much less than would be expected for the volume of sediment pond. Consequently, sufficient settling time is not achieved and the effluent quality is less than expected.

Short circuiting can result from high inlet and/or outlet velocities, close proximity of inlet and outlet structures to one another, basin geometry, and density differences between the influent and permanent pool. Density differences can be due to temperature differences as well as salt or sediment concentration differences.

Short circuiting is undesirable because it causes ineffective use of the pond volume and produces an effluent of lower quality than expected. Skelly and Loy[27] present a short-circuiting correction factor for the surface loading rate equation. An explanation of the equation without the correction factor will be presented in the section on pond size. (see Eq. 5) The modified version is as follows:

$$A = F_{sc} \frac{Q}{V_s}$$

Where: A = Design surface area

Q = Flow

V_s = Design settling velocity

F_{sc} = Short circuiting factor

Table 3 below gives the suggested values for the short-circuiting factors for different shaped ponds.

TABLE 3. SHORT CIRCUITING FACTORS FOR SETTLING TANKS (taken from Skelly and Loy[27])

Type of Tank	Short Circuiting Factor (F_{sc})
Radial-flow circular	1.2
Wide rectangular (length = 2.4 x width)	1.18
Narrow rectangular (length = 17 x width)	1.11
Baffled mixing chamber (length = 528 x width)	1.01
Ideal basin	1.0

Kathuria et al.[37] show a similar table and describe the short-circuiting factor as a reciprocal of ta/T. Where "ta" is the probable flow-through time of the water through the pond; and "T" is the theoretical detention time. The sections on pond shape, inlet and outlet structures and baffles will all address the short-circuiting problems.

Another problem which frequently is experienced in sediment ponds is scour and resuspension which occurs when the horizontal velocity of the runoff passing through a sediment pond is sufficient to cause previously deposited sediment to be picked up and carried out of the pond by the effluent. Cases of severe scour have been reported where the sediment concentration of the effluent is greater than the influent.

To prevent scour, it is necessary to keep the horizontal velocity through the basin below the critical velocity required to cause scour. This velocity, called the scour velocity, is defined by Kathuria et al.[37] as follows:

$$v_c = \sqrt{\frac{8B}{F} g (S_s - 1) D} \qquad \text{EQ. 4}$$

Where: v_c = scour velocity, cm/sec.

B = .04 for unigranular sand
$\geq$ .06 for sticky, interlocking material

F = .02 to .03, friction factor

g = acceleration due to gravity, cm/sec.^{2}

S_s = specific gravity of the particle

D = diameter of a spherical particle, cm

Ingersoll et al.[91] suggest that to avoid scour the forward velocity be limited, as a rule of thumb, to between 9 and 15 times the critical settling velocity.

Methods will be discussed in the following sections which are used to dissipate energy and reduce velocities so as to prevent scour. Additionally, scour will become a greater problem when the elevation of the deposited sediment nears the outlet structure opening. To prevent serious scour problems when this happens, it is necessary to remove the sediment from the pond. Nawrocki[92] reports from his study of sediment pond effectiveness that, ". . . resuspension of settled sediment was rarely observed in ponds where the water depth was greater than approximately 1 meter (3.3 ft.)."

Turbulence within the pond will reduce sediment removal efficiency. Murray[93] reports that, "The average settling velocity of a particle in turbulent water can be considerably reduced below its terminal settling velocity in still water." Inlet and outlet structure design are probably the most important factors in reducing turbulence within the pond.

As stated above, cleaning out of accumulated sediment deposits will be an important factor in maintaining pond efficiency. In the section on pond size, which will follow, government regulations will be discussed which will require that sediment deposits be removed when the original sediment storage volume has been reduced by a specified percent. Sediment can be removed from ponds by draglines or if the ponds are dry, by front end loaders or dozers. Smaller ponds in series may require more frequent cleaning, but will generally be easier to drain to facilitate cleaning. In addition, generally only the first pond which traps the larger particles will require cleaning. Off-channel ponds which have no base flow will likewise be able to be easily drained. In-channel ponds are likely to have a continuous base flow and care must be exercised so that sediment stirred up during cleanout operations is not washed down stream in the base flow. Thus clean out procedures are an important consideration when determining location, type, size, and number of ponds.

Unless approved by the regulatory agency, all ponds will

need to be removed once the disturbed area has been restored and influent quality meets the required standards. Pond removal requires special care also. Especially in the case of in-stream ponds, care must be exercised such that deposited sediment is not allowed to be washed down stream. The relative ease in closing down off-channel ponds is a big factor which favors their selection in favor of in-channel ponds.

DESIGN CRITERIA AND CONSIDERATIONS

Each of the aspects of pond design will now be reviewed in the light of the frequently experienced problems, clean out and close down procedures just mentioned. New methods and techniques, as reported in the literature, as well as the commonly used practices, will be presented. It is felt that this material comprises the current State of the Art for sediment pond design for use on surface mined land.

POND SIZE

Ponds must be designed to handle both the hydraulic load and the sediment load. In designing for the hydraulic load the concern is that the pond will be physically large enough to pass the design storm without causing the dam or embankment to fail. The Office of Surface Mining[14] (OSM) specifies by regulation the design storm to be a 25-year, 24-hour event unless the embankment dam is greater than 20 feet (6.09 m), or the storage volume is greater than 20 acre-ft. (1233.48 cu. m). If either of these limits are exceeded, the design storm will be a 100-year, 24-hour event. In either case, the principal and emergency spillways must be capable of safely passing the design storm.

The method for assuring that a pond or reservoir can safely pass a particular storm is known as reservoir routing. The mechanics for reservoir routing are well established. For reservoir routing, it will first be necessary to select or synthesize a design hyetograph as mentioned in Chapter II. From this, the inflow hydrograph is developed. Other required information is the stage-volume curve and the outlet's hydraulic characteristics. The compiling of all of this required information is straight forward with the exception of the design hyetograph and hydrograph. Two general methods exist for obtaining design hyetographs. (see Chapter II) and it is speculative as to which is the best approach. Several methods also exist for obtaining the hydrographs. Reasonable results are obtained from all methods mentioned in

Chapter II. The selection of the specific method is left to the discretion of the design engineer.

In determining the size of ponds to meet the sediment load requirement, two criteria are normally specified by regulations: 1) sediment storage requirements, and 2) volume sufficient to yield the specified detention time. The sediment storage volume, sometimes referred to as the permanent pool storage, is the estimated storage volume required to hold the trapped sediment. As sediment is trapped, it settles and accumulates at the bottom of the pond. Thus the total volume of the pond decreases with time. As the volume decreases, so does the detention time and trap efficiency. Once the volume occupied by the trapped sediment becomes larger than the design sediment storage volume, the trap efficiency will become adversely affected. For proper operation, the pond will need to be cleaned out at this point.

Ponds are either designed to store the total amount of trapped sediment expected for the life span of the pond, or they are designed for periodic cleaning. Sediment yield, trap efficiency and storage volume will determine the frequency of cleaning. The larger the sediment storage volume is, the less frequently cleaning will be required. However, larger storage volumes usually increase construction costs; therefore, construction costs and cleaning costs will need to be weighed against each other.

Minimum storage requirements are usually set by regulatory agencies or recommended as local guidelines. These recommended guidelines or minimum requirements vary among the states. OSM has also set minimum requirements which state regulations must meet or exceed. Summarized in Table 4 is a sampling of some of the existing regulations and guidelines.

Sediment storage requirements are normally expressed in one of two ways. They can be expressed as a specified volume per each arce of either disturbed or drained land. (i.e. 1.5 m^3/ha disturbed, or 1.25 m^3/ha drained) Another method of expressing sediment volume is to specify that the storage volume must be sufficient to hold the expected accumulation of sediment over a specified time period. (i.e. the storage volume must be sufficient to hold the expected sediment yield over a 3-year period) Normally the means of calculating the expected sediment yield is also specified when this method of specifing storage volume is used.

Table 4. Sediment Storage Volumes

Agency/State	Criteria	Remarks
OSM[14, a]	Accumulative sediment volume from drainage area for a minimum of 3 years[b] or .1 acre-foot for each acre (304.8m³/ha) of disturbed area or .035 acre-foot for each acre (106.7m³/ha) of disturbed area if operator demonstrates that sediment removal by other methods equals the reduction of sediment storage volume	a- Published March 1979 b- Accumulatice sediment volume is to be determined by USLE
USDA, SCS[94] Columbus, Ohio[c]	200 cubic yards/acre (377.8m³/ha) of disturbed land[d] Clean out required when design capacity reduced by 60%	c- Published June 1978 d- Standards are for temporary sediment pond, dam height ≤25 ft. (7.62m), total volume ≤150 acre-feet (1.8 X 10⁵m³), drain-area 100 acres (40.47ha) (for urban areas)
Maryland[37, e]	.5 inches/acre (3.138cm/ha) drained[f] .2 inches/acre (1.255cm/ha) drained[g]	e- Source document published August 1976 f- Total storage-to crest of emergency spillway, or pipe spillway if there is no emergency spillway g- To be cleaned when storage capacity drops below .2 inches/acre (1.2cm/ha)
Kentucky[37]	.2 acre-feet/acre (609.5m³/ha) disturbed	
West Virginia[37]	.125 acre-feet/acre (15.38m³) disturbed Clean out required when design capacity is reduced by 60%	
Pennsylvania[37]	V = (AIC) + (AIC/3) V = Volume, cubic feet A = Area drained I = Rainfall/24 hours C = Runoff constant = % of rainfall not absorbed by soils	
Consulting Engineer Rockville, Md. [95, i] (recommendations)	600 cubic feet/tributary acre, minimum depth of 1 foot (.305m)[h]	h- This is strictly sediment volume storage, additional 1.5 feet (.46m) minimum settling volume recommended above sediment storage (for construction sites) i- Published July 1975
Research Specialist University of Kentucky[96, j] (recommendations)	.015-.085 acre-feet (18.45-104.55m³) of permanent pool storage for each acre of watershed area (disturbed or undisturbed)[k]	j- Published December 1978 k- For Appalachia watersheds based on 2-year, 2-hour event

It should be noted that no specific storage requirement is universally agreed upon. The reasons for these variation may be attributed to different expected sediment yields due to differences in soil and/or topography of different geographical locations. Also, the recommendations/requirements quoted in Table 3 cover three different sediment sources: urban areas, construction sites and surface mined areas. These different sources may also lead to different expected sediment yields. Probably the main reason for non-uniformity of storage requirements is the difference of opinion of its relative effect on trap efficiency. The established or recommended storage values are generally based on field experience. Since experiences differ due to different type ponds observed in different locations, it is only reasonable to expect that recommended storage volumes will differ from location to location.

The OSM regulations have established uniform criteria throughout the country by specifying storage requirements in terms of sediment yield volume per specified period of time. Furthermore, the regulation specifies the method to be used to predict sediment yield volumes. It is interesting to note however, that the method specified for predicting sediment yield, that is the USLE, has not as yet been verified for use in surface mined areas. It will be remembered that it was developed for agricultural land and although it has been used elsewhere, i.e. construction sites, much research is still underway to determine its applicability for surface mined areas. Also, erodibility, length/slope and land management factors for surface mined areas need to be determined or verified.

The other criteria for determining pond size, for water quality purposes, is detention time. The detention time is the amount of time water is detained in the sediment pond. Consequently, it is the amount of time that the sediment has to settle. Therefore, the longer the detention time is, the more sediment will be trapped. For this reason, detention time is used as an indicator of the trapping ability of a sediment pond. Unfortunately, detention time varies throughout the routing of a flow through a reservoir or pond. To simplify matters, an average detention time is used. A commonly used definition for this average detention time, and the one used in the OSM[14] regulations is, ". . . the time difference between the centroid of the inflow hydrograph and the centroid of the outflow hydrograph . . ." Although this definition makes the calculation of the detention time relatively easy, it actually distorts its ability to act as a sediment trap efficiency indicator. Nesbitt and Notary[197] point out that to increase the detention time, it is necessary to reduce the peak of the outflow hydrograph and to stretch

its time base out over as long of a time period as possible. To do this, the pipe size and riser size of the principal spillway are reduced in size to provide for a slow drainage of the pond. However, to avoid dams of excessive heights, the crest of the principal spillway is lowered as far as the regulations will allow. This reduces the permanent pool to a size equal to the required sediment storage. By doing this, the crest of the primary spillway is closer to the deposited sediment increasing chances of resuspension; it also allows drainage of the high sediment concentrated water near the bottom.

The point is that detention times can be numerically maximized without necessarily increasing trap efficiency or effluent quality. In fact, effluent quality may be substantially reduced. Also, this definition of detention time does not adequately indicate the improvement to water quality that may be achieved by employing ponds in series. Ponds in series may improve effluent quality, but the individual ponds are smaller in size and will have considerably shorter detention times.

Nesbitt feels that the regulations should give credit for trap efficiency improvement provided by permanent pools. This author has found no reports of research completed or in progress that is attempting to quantify the benefits of permanent pools. Intuitively, permanent pools aid against resuspension by protecting the deposited material from the incoming flow. Furthermore, if ideal plug flow existed, that is, the entire permanent pond is drained prior to any of the new flow draining, than substantial detention time would be gained. However, ideal flow does not occur and there is a mixing of new flow with the permanent pool. The extent of mixing is not known however. Ward and Haan[96] concluded from their study of sediment ponds in Kentucky that pond performance can be improved by increasing the permanent pool size. Again, no quantitative relationship between permanent pool size and water quality was determined.

Currently, the OSM regulations require a detention time of not less than 24 hours for a 10-year, 24-hour precipitation event. There are three exceptions to this requirement, all of which require demonstration by the operator that effluent standards are met. Thus, the detention time requirements need not be met as long as effluent standards are met. On the other hand, even if the detention time requirement of 24 hours is met, the operator is still required to meet effluent standards. The point is that even if the detention time as defined is not a good indicator of the effluent quality to be expected, the OSM regulations do not severely hamper the operators' iniative in finding economical means of controlling

sediment nor do they relieve him of responsibility of achieving effluent standards by merely meeting the detention time requirements.

Another method used to determine pond size involves the surface loading rate. The surface loading rate is equal to the flow rate through the pond divided by the surface area of the pond.

$$V_s = Q/A \qquad \text{EQ. 5 (Taken from Kathuris et al.[37])}$$

Where: Q = flow rate

A = surface area

V_s = surface loading rate

Note that the flow rate divided by the surface area is equal to the depth divided by detention time. This is exactly the minimum settling velocity that a particle must have in order to settle to the bottom and avoid being discharged. It can be seen then that the surface loading rate is equal to the critical settling velocity. The critical settling velocity can be determined by selecting the smallest size particle that is to be trapped. Then, since the flow rate is determined from the outlet design, Equation 5 can be solved to find the required surface area. This of course is the required surface area for ideal settling. It does not take into account resuspension due to inlet and outlet disturbances, short circuiting, etc. In an EPA design manual[69], it is suggested that a 1.2 correction factor be applied to compensate for non ideal settling. It will also be remembered that Skelly and Loy[27] recommended a modification to Equation 5 (see Eq. 4) to correct for short circuiting based on pond geometry.

The surface loading rate method is more practical for use in sewage and water treatment plants where the basins are regular in shape with uniform depths, widths and flow rates. The sediment ponds for surface mined areas reported on in the literature are normally of irregular shape which are a function of the particular terrain rather than any design consideration. More attention has been paid to volume and detention time than has been paid to the surface area or shape.

To summarize design considerations for pond sizes, it is seen that ponds are designed for both hydraulic and sediment loads. Hydraulic loads to be designed for are specified by Federal and State regulations. Procedures for the hydraulic

design are well estabilished. The only area left to speculation is in choosing the method to obtain the design hyetographs and hydrographs.

The sediment load design factors are divided into two areas: 1) sediment storage volume requirements, and 2) settling volume required to give the sediment sufficient time to settle. The sediment storage volume is either set by regulations or local guidelines. The volume requirement can also be found by calculating the expected sediment yield over the design life of the pond. Sediment yield can be found by several methods, however OSM regulations stipulate the use of the USLE. It should be kept in mind that the USLE has not yet been verified for use in surface mined areas. Nevertheless, it is reasonable to believe that the USLE can be successfully used for surface mined land. However, values for the soil erodibility, length-slope, and management factors are not presently available for the different conditions found in surface mined areas.

The methods used to determine volume requirements to assure sufficient time for sediment settling are not fully adequate. The surface loading method is best suited for permanent uniform basins. Detention time as a trap efficiency indicator can be misleading. A design procedure for sizing ponds to assure sufficient time for settling is needed. Irregular shapes, non uniform depths, fluctuating flow rates and sediment concentrations have thus far hindered the development of an acceptable procedure.

NUMBER OF PONDS

Ponds can be and have been used in series. The primary reasons for their use to date, as reported in the literature, is for two reasons. One is the use of a small pond to pretreat the runoff to remove the larger particles prior to the runoff entering the primary pond. The other reason is to use the first pond for settling of large particles and the addition of chemical coagulants, while the second pond is used for flocculation and final settling. The only reference found during this study which gives details about sediment ponds in series is the EPA[69] design manual for sediment erosion control. It lists the following features of ponds in series:

a) can be employed where topography does not permit the construction of one large pond,

b) may increase detention time and suspended solid removal,

c) one pond can be used to pretreat the runoff to remove the larger particles before they reach the primary settling pond,

d) clean out of smaller ponds is generally easier and can be accomplished with common equipment, i.e., bucketloader or dozer,

e) small ponds can be removed more easily,

f) wave disturbances and bank erosion due to wind is minimized with smaller ponds, and

g) several smaller ponds may require more excavation than one large pond; however, dam construction for a larger pond may be more expensive than the difference in excavation costs.

The considerations for using several small ponds in series opposed to one large pond will have to be made on a case by case basis. There has been little reported in the literature about the effectiveness of ponds in series. No reference has been found on how to determine detention time for the composite system. It is unlikely that the detention times of each individual pond would be additive since the transition between ponds is likely to disrupt the settling process. A report titled, Effectiveness of Surface Mine Sedimentation Ponds,[37] presents the effectiveness of six sediment ponds, two of which have two ponds in series. However, due to the many other factors involved in trap efficiency, the effects of using two ponds in series could not be determined from this study.

In summary, there are some very practical reasons for employing ponds in series; these include: limitations of the topography for constructing one larger pond, cost and maintenance factors, and smaller surface area to be affected by wind. This study however, has found no report of ponds in series providing higher effluent quality than single larger ponds or vice versa.

POND SHAPE

In discussing pond shape two descriptions can be considered, the length/width ratio and the geometric form of the surface. The length/width ratio will be discussed first.

The length/width ratio is used as a rule of thumb in pond design to help minimize the effects of short circuiting. The greater the length to width ratio is, the less is

the chance of short circuiting. Length/width ratios have been based on experience with little if any formal research to quantify it. Thus, as might be expected, there is a wide variance in recommended values. Table 5 shows recommended values which were found in the literature. For irregularly shaped ponds, the effective width is determined by dividing the surface area by the length of the path actually traveled (effective length) by the flow. To reduce short circuiting, baffles are sometimes employed to lengthen the actual flow path of the water. These will be discussed in more detail later. The author has found no reference to length/width ratios by any regulatory agency.

TABLE 5. RECOMMENDED LENGTH/WIDTH RATIOS

Source	Length/Width Ratio
Erosion and Sediment Control, Surface Mining in the Eastern U.S.,[69] EPA-625/3-76-006	at least 2:1
Water Management and Sediment Control for Urbanizing Areas,[94] USDA, SCS, Columbus, Ohio	at least 2:1
Standards for Soil Erosion and Sediment Control in New Jersey[72]	2:1
Standard and Specifications for Sediment Basin, USDA, SCS, Md.[99]	2:1
Design of Sediment Basins for Construction Sites,[95] by P.C. Oscanyan, Consulting Engineer	at least 4:1
Development of Methods to Improve Performance of Surface Mine Sediment Basins,[27] by Skelly and Loy, Engineers-Consultants	5:1

Most sediment ponds for surface mine areas reported in the literature are of irregular shape, taking their shape from the particular terrain selected for the pond site. Not much information has been found in the literature regarding the effect of shape on pond performance. Intuitively, the desirability for longer detention time translates to slow flow rates and long effective pond lengths. However, it is

desirable to know what, if any, geometric shape will provide the best hydraulic flow characteristics to yield the best effluent.

This study has found only two references which make recommedations as to the geometric shape of the pond. Both articles were related to sediment ponds in irrigation systems and have the same author or coauthor. Each recommends a different geometric shape. The first article published in 1975 by Bondurant et al.[100] recommends triangular shaped ponds. The desirable pond characteristics are given as ". . . design should provide maximum velocity reduction early in ponding, allow adequate storage space for the larger particles, and decrease the flow depth toward the outlet while maintaining a constant forward velocity. This requires a fan-shaped pond, deeper at the inlet and decreasing in depth while increasing in width toward the outlet." The authors indicate that triangular shaped ponds would fit well into natural draws or swales.

In 1977 Bondurant[101] published another article in which he recommended rectangular ponds while making no reference to triangular ones. He recommends a length/width ratio of at least 4 to 1, the piped inlet to be centered in the inlet section, and full width exit sections.

The sediment ponds reviewed and reported on by the EPA in reference 37 included rectangular and round ponds. However, the study was not aimed at finding the best hydraulic conditions for sediment removal, and no inference can be drawn about geometric shapes.

In summary, the shape of sediment ponds normally found in surface mined areas are irregular. Guidelines or rules of thumb indicate that the length/width ratio be anywhere from at least 2:1 to 5:1 or greater. No shape requirements have been found in governing regulations, reviewed in this study.

INLET DESIGN

Three principal functions of inlets can be discerned: 1) to dissipate energy, 2) to distribute flow across pond width, and 3) to filter the influent. The purpose of dissipating energy is to reduce the sediment carrying capacity by reducing the velocity and turbulence and thus causing immediate deposition of the larger sediment particles. This early reduction of flow velocity also maximizes the time available for the smaller particles to settle.

Studies by Kathuria et al.[37], and Ward and Haan[96] suggest the use of energy dissipators at inlets to improve pond efficiencies. Energy dissipatation can be achieved by placing obstructions in the flow path in the form of dumped rock, log or pole structures, check dams or baffles. Baffles will be discussed later. Log or pole structures and check dams have been mentioned and referenced earlier. Their use will more than likely create a small pond in front of the main pond which will act as a pretreatment pond.

Distribution of flow across the width of the basin increases the effective cross-sectional area which reduces the velocity and possible short circuiting, and increases detention time. Methods of distributing flow include: apron inlets, baffles, and multiple inlets. Apron inlets act similar to level spreaders discussed in Chapter III. They provide a transition of decreasing depth and increasing width between the channel and the pond. Reference 27 mentions this type of inlet design and provides a diagram. Baffles will be discussed later and multiple inlets are self-explanatory. Reference 27 provides a diagram of one possible method. If no provisions are made for the distribution of flow, single inlets should at least be located so as to provide the longest travel distance to the outlet.

Filtration of the influent is limited to drainage from small areas, and for off-channel ponds. This limitation is due to the extremely slow rate of filtration. Two means of filtration suggested by Skelly and Loy[27] are the use of straw bales or silt fences. It appears to this author, that this type of filtration will cause ponding in front of the primary pond which will act as a pretreatment settling pond. No reference was found in the regulations reviewed requiring any particular type of inlet design.

OUTLET DESIGN

Outlets are often referred to as spillways. Most ponds of any size have two spillways: the principal spillway and the emergency spillway. When a pond has both principal and emergency spillways, the primary spillway is to be designed to handle the design storm for water quality purposes. The combined discharge of the principal and emergency spillways are to be able to safely pass the design storm for which the embankment is designed. The specific design storms as established by OSM were presented in Chapter II.

The hydraulics for different outlet structures are well established. Haan and Barfield[15] give the head-discharge

relationship for the typical discharge structures. To determine if the discharge outlets will safely pass the design storm, a reservoir routing technique, as discussed in the section on pond size, is used.

Besides meeting the hydraulic requirements necessary to safely pass design storms, outlet structure design needs to consider water quality as well. Detention time is dependent on the discharge rate of the outlet structure. The relationship of detention time and water quality was discussed in the section on pond size.

In most cases, it is desirable for the outlet structure to withdraw water from the surface of the pond. It is generally accepted that the clearest or highest quality water is at the surface. However, Glazier[102] indicates that the water at the surface sometimes will experience higher suspended solid concentrations than water below the surface. Glazier suggests that this might be due to algae formed on the surface. This has yet to be proven by experiment or field studies, and if it is shown to be true, it will likely be seasonal and dependent on nutrient content, etc. For inorganic suspended solids, the settling theory indicates that the higher quality water will be at the surface and as such, it is presently felt that superior results are obtained when effluent is withdrawn from the surface.

The other aspect of outlet design which affects water quality is dewatering methods. Frequently, it is desirable to draw the water level down below the level of the principal spillway crest to provide more storage for the next runoff event. This is called dewatering. However, Ward et al.[34] recommends, ". . . that dewatering be minimized as much as possible as a large permanent pool provides the most favorable trapping characteristics. Dewatering also requires the withdrawal of some of the poorest quality of flow."

If dewatering is required, the following methods are available:

1) manually opened dewatering devices,
2) perforated risers/single perforation dewatering devices,
3) siphon draw downs, and
4) subsurface drains.

Ward and Haan[96] recommend manually opened dewatering devices for use with riser pipe spillways. Ward et al.[34] suggest that, ". . . a series of orifices with shuttered ports could be located along the length of a vertical riser. As the flow

within the pond clarifies, each port would be opened." This would allow a higher quality effluent to be discharged, and at the same time provide a means of lowering the permanent pool to provide more storage for the next runoff event. Another advantage of a manual system is that dewatering orifices can be located below the level of the sediment storage pool. This allows for complete dewatering during cleaning operations.

Perforated risers are perhaps the least desirable of dewatering devices available. Single perforation dewatering devices differ from perforated risers in that a single perforation is located at the sediment cleanout level. A perforated riser has multiple openings (usually slots) stagger from the sediment cleanout level to the top of the riser. Both methods are undesirable since they do not allow for storage as the water level is rising, and withdraw poor quality subsurface water during high flow events (see Figure 7). References 69 and 27 show a single perforation dewatering device with and without skimmers. Single perforation without skimmers are subject to clogging.

Siphon draw down devices allow pond levels to be reduced below the principal spillway crest automatically without the use of perforations. Although these devices withdraw water from below the surface, they do allow for storage prior to drainage. Consequently, better quality effluent is expected. Reference 27 and 69 discuss and illustrate siphon drawdowns.

All three risers shown in Figure 6 will lower the pond level to the dotted line labeled "A." Figure "a" depicts a single perforation drawdown. Base flows will begin to be withdrawn from the surface when the level rises above line "A." Withdrawal will be subsurface when the level rises above point B. The perforation is usually 3-4 inches (7.62-10.16 cm) in diameter. If no skimmer is provided, it will be susceptable to clogging by floating debris.

Figures b and c show short and long siphon drawdowns respectively. Both have a discharge rate higher than the single perforation drawdown. The short siphon will begin discharging when the pond level reaches point "c." The only storage provided for the base flow is indicated by E. Withdrawal for both siphons will always be subsurface. The long siphon will not begin discharging until the pond level reaches point "D." The advantage of the long siphon is that it provides storage for the baseflow. The time it takes the baseflow to raise the pond level through the height indicated by "F" is the detention time which this system provides for the baseflow.

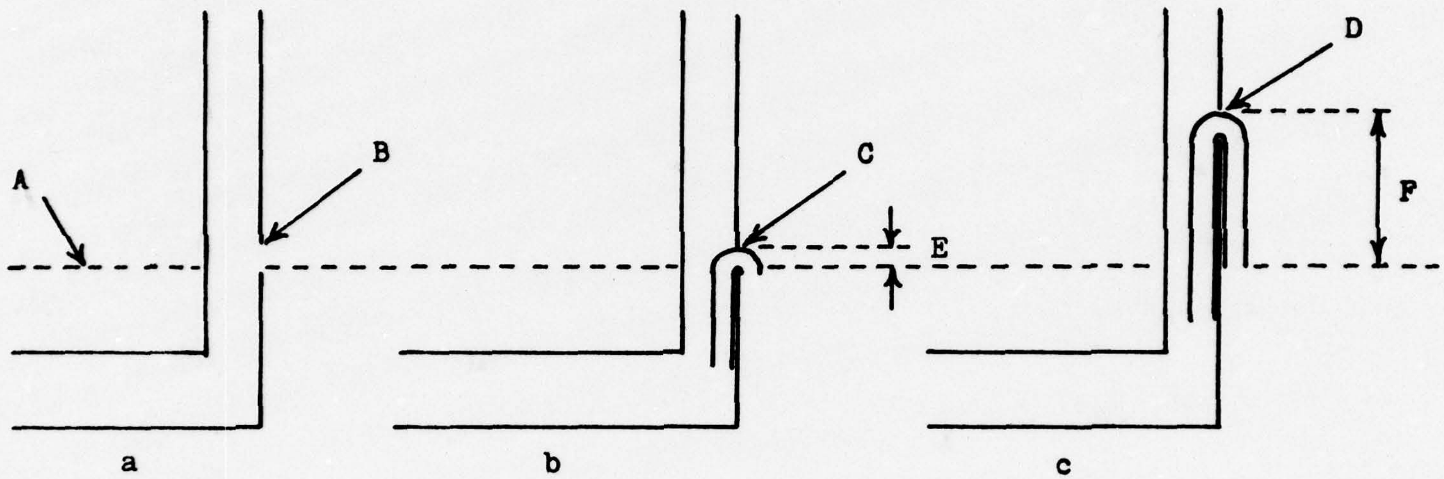


Figure 6. Risers With Draw Down Devices
(modified from Reference 69)

Subsurface drains consist of a network of perforated drain pipes buried below the pond. This author has found no reports on the actual performance of this type of system. It would be suspected that clogging might be a serious problem. References 69 and 27 illustrate this method of dewatering.

Another aspect in outlet design is location. As with inlet design, the outlet should be located to minimize short circuiting and to maximize travel distance and time. Basically, this means to physically separate the inlet and outlet as far apart as possible.

There are several types of outlet structures commonly used in sediment ponds. They include perforated and non perporated riser pipes, troughs, weirs and vegetated channel spillways.

Perforated or non perforated riser pipes are generally constructed from either corrugated metal pipe or plastic pipe. They are connected to a horizontal pipe conduit which extends beyond the downstream toe of the embankment. The base of the riser is often made of concrete sufficiently large to prevent floatation. Although concrete bases are not required, some means of anchoring the riser and pipe to counteract the buoyancy force is necessary. Riser and pipe sizes will determine discharge rates and thus their sizes will be determined during reservoir routing design procedures. Some publications recommend minimum sizes. For example, California's EPA manual[70] for erosion and sediment control recommends a 12 inch (30.48 cm) minimum diameter for horizontal pipes and a 30 inch (76.2 cm) minimum diameter for risers. The SCS's "Standard and Specifications for Sediment Basin"[99] for Maryland does not specify minimum pipe diameters, but requires the principal spillway to be capable of passing .2 cfs/acre (.014 meter^3/sec./ha) of drainage area when the water level is at the emergency spillway crest elevation. (Note: references 70 and 99 refer primarily to construction sites)

Linderman et al.[103] recommend that care be taken to assure that the flow through the horizontal pipe does not flow under pressure. The reason he gives for this is that, ". . . its capacity is less and reverse flow may occur through risers at lower elevations." Regardless of whether or not "reverse flow" occurs, the capacity will be reduced and this must be considered in the reservoir routing work to assure that the embankment structure is not over topped during the design storm. Instead of altering the stage-discharge curve for pipe flow conditions, it is easier to insure that pressure flow does not occur and thus allow discharge to be governed

solely by weir or orifice capacities.

Two modifications are frequently incorporated with riser spillways. These are trash racks and antivortex devices. Trash racks prevent floating debris from entering and clogging the riser, while antivortex devices prevent the high velocities, surface disturbances, and capacity reductions associated with vortices caused by the Coriolis force. Both functions are usually combined in one device. For specifications on trash racks and antivortex devices, the reader is referred to references 69, 70 and 99.

A frame similar in shape to an antivortex device, but much larger (10ft x 10ft x 3ft) (3.05m x 3.05m x .91m) with the intended purpose of preventing short circuiting, has been tested by Jenkins and Pankanin[104] in conjunction with riser pipes. The testing of this device, conducted at West Virginia University, proved the device to be unsuccessful. However, the investigators feel that with some modifications, it might be of some future use. For details on the device and its testing, see reference 104.

In an attempt to improve the effluent quality of perforated risers, filters have been tested. Sediment removal efficiency was improved when risers were wrapped with various types of filter membrane, but experience shows that the filters become clogged too rapidly for practical use. For more detail on the testing of riser filters, the reader is referred to reference 95.

Non perforated risers are recommended by nearly all agencies and researchers. If perforated risers are to be used, recommended sizes are given in references 70, 96 and 103.

Another type of outlet structure being tested and used more frequently are full width skimming weirs and troughs. Bondurant[100] recommends the use of full-width skimming-type weir outlets to provide uniform overflow depths and prevent short circuiting. Jenkins and Pankanin[104] experimented with a 24ft (7.31m) long wooden trough which they secured to the top of a riser. The front of the trough was an adjustable weir with 90 degree V-notches. One of the main problems encountered was the buoyancy of the wooden trough. The buoyant forces made it difficult to keep the trough level and uniform overflow depths were not maintained. Skelly and Loy[27] show design sketches for a wooden weir trough with a maximum length of 100ft (30.48m). This trough is likewise secured to the top of an outlet riser.

A somewhat recently proposed technique to be used in conjunction with discharge troughs involves the use of commer-

cially manufactured[134] fiberglass body structure outlet units. These, so called, filters, are 12 inches (30.48cm) in diameter and 16 inches (40.64cm) high, with a flow through capacity of 60,000 gph (227.12m^3/hr). They actually operate on a skimming weir principle, rather than as a filter media, with over 150 feet (45.72m) of effective weir in each unit. It is suggested that these units be installed such that their effluent empties into the discharge troughs. They have been successfully used in septic tanks for the past 15 years, and have recently been recommended for use in sediment ponds. No reports have been found in the literature about its use.

Other outlets include lined channels which are normally used for emergency spillways. These can vary from expensive concrete spillways as found on larger reservoirs to riprap or vegetative lined channels. References 49, 70 and 72 illustrate concrete chute spillways, and reference 69 gives design criteria for earth spillways.

Multiple outlets and baffles can be employed to increase pond performance by preventing or reducing short circuiting.

Finally, protection must be provided for the receiving channel or waterway where the spillway discharges. Standard procedures are available for this, and include: concrete aprons and riprap. Reference 69 gives more details on these methods.

In summary, outlet designs must meet the requirements set by government regulations to safely pass design storms and also to provide for sufficient detention time. To assure that these conditions are met, reservoir routing techniques, either graphical or computerized, can be used. Considerations for outlet locations are the same as for inlet locations, that is to maximize travel distance through the pond, and minimize short circuiting and dead space. The typical types of outlet structures are risers with drain pipes, skimming weirs and troughs, and lined spillway channels. Of these, full width skimming weirs and troughs are theoretically best suited for preventing short circuiting and should give superior results in water quality. However, the only report found in this study on their actual performance indicated problems associated with trough buoyancy. Regardless of the type of outlet used, it is a generally accepted belief that for best results, effluent should be withdrawn from the surface.

Four methods of dewatering ponds below the level of the primary spillway crest were mentioned. The one which provides excellent results in terms of water quality is the manually opened drain. The obvious drawback is that it requires

an attendant's presence after each runoff event. Perforated risers and single perforated risers reduce effluent quality by passing subsurface water and providing no storage for base flows. The single perforated riser's performance can be improved somewhat by installation of a long siphon which will provide some storage before passing base flows. Finally, subsurface drains were mentioned. They appear to potentially provide excellent effluent quality, but no reports on their actual performance were found during this study. This author anticipates that cost or clogging problems may eliminate it as a practical solution.

BAFFLES

Baffles have been mentioned in previous sections, but will be discussed here in greater detail. Baffles are artificial barriers used in sediment ponds for the purpose of dissipating energy or directing flow. They can be used at inlet structures to dissipate energy and cause the formation of a forebay where larger particles are removed by settling. For this reason, a low overflow baffle extending across the width of the pond would be used. This type of baffle would also serve to evenly distribute flow across the pond width.

Another type of baffle which can be used at the inlet is directional baffles. These baffles are usually higher, but do not extend across the full width of the pond. Their purpose is to direct flow so as to increase flow length and minimize short circuiting. Care should be taken so that baffles do not direct flow against unprotected banks and thus cause bank erosion.

Directional baffles can be employed also at outlet structures or anywhere throughout the pond to increase the effective length/width ratio and reduce short circuiting.

Baffles are normally constructed from logs and poles, rough sawed lumber, or exterior plywood. References 27, 34 and 69 give details on baffle construction and illustrate their possible locations on hypothetical irregular shaped ponds.

Jenkins and Pankanin[104] have experimented with a baffle constructed using 4.5ft x 75ft (1.4m x 22.9m) impermeable plastic brattice cloth. The plastic cloth sections were supported by floating logs while their lower corners were held down by weights. The logs were connected together by rope and stretched across the entire width of the pond. Sufficient data had not been collected by the time that Jenkins

and Pankanin presented their paper in May of 1979 for conclusive results to be drawn as to the effectiveness of this method. However, indications are that its use may be credited with reducing short circuiting.

FLOCCULATION/COAGULATION

Flocculation/coagulation processes have been proposed, and have received limited use for the removal of colloidal suspensions from surface mine runoff. In areas where the sediment contains clay, it is nearly impossible to meet water quality standards by settling alone, unless the clay content is extremely low.

Flocculation requires the addition of a coagulant which causes the particles to form aggregates. The increased size of the aggregates give them a greater settling velocity than that of the individual colloidal particles. This increase in settling velocity is sufficient to allow the aggregates to settle within a reasonable amount of time.

The first task in setting up this process is to select the proper coagulant. McCarthy[98] mentions two polyelectrolytes by their trade names; both provided successful results for a sediment pond built near Centralia, Washington. Skelly and Loy[27] reported on their investigation of 31 coagulants selected from an initial list of 144. In their draft report to EPA, they show the results of their testing and rank the seven best coagulants according to their overall performance. The final test of the coagulants was to determine their environmental impact. Laboratory studies indicated that for the coagulants tested, little or no impact to the environment would be experienced.

This author has not found any study which shows effectiveness of specific coagulants for particular sediment types. Thus, for each area where coagulants are to be used, laboratory and field tests must be run to determine effectiveness and dosage rates. Skelly and Loy[27] propose the following procedure be used in selecting coagulants: 1) Contact manufacturers for coagulant characteristics and begin initial screening process for the most applicable products. 2) Conduct preliminary laboratory tests to determine the effectiveness of each coagulant in removal of suspended solids from effluent samples taken from the pond in question. 3) Determine by laboratory testing the relationship between percent removal and coagulant dosage rate for each of the 5-7 coagulants selected from Step 2. 4) Determine the cold weather effects on each of the coagulants.

In addition, tests will need to be run to determine the environment impact of using these coagulants. In their tests, Skelly and Loy analyzed water samples for total dissolved solids, total organic carbon and chemical oxygen demand. As stated earlier, their tests indicated little or no impact to the environment would be experienced. For further details on their tests and the results, see reference 27.

The procedure for using coagulants involves the addition of the coagulant with rapid mixing followed by a very slow mixing which allows particles to aggregate and a period of relative quiet flow to allow the aggregates to settle. A series of ponds are normally employed when coagulants are used. The first pond provides preliminary settling to remove the larger particles. This preliminary settling will prevent the larger particles from interfering with the coagulation process and requiring larger dosages of chemical additives. The chemicals are normally added as the water leaves the preliminary pond. If sufficient head exists, a water fall-step-method can be used to agitate the water to provide rapid mixing. The steps can be constructed from rock or logs. In the set up described by McCarthy[98], a 50 foot (15.24m) long, half round culvert with baffles placed every 5 feet (1.524m) provided the required rapid mixing. Skelly and Loy[27] suggest that the slow mixing be provided for by placing directional baffles in the first 1/3 section of the second pond. The baffles should be arranged in such a manner as to cause a snake like flow pattern. The final 2/3 of the pond is then used for quiescent settling.

The use of coagulants in surface mine sediment ponds has not received wide acceptance. The reason is not because it is not needed, for it is the general opinion and experience of the researchers and consulting engineers with whom this author has talked, that sediment ponds alone will not achieve the effluent quality standards for designed storms. Some of the possible reasons for not using coagulants is expense, maintenance problems, lack of available design criteria, and the lack of adequate chemical application methods.

Although this author did not review the original paper presented by McCarthy at the 1977 National Symposium on Soil Erosion and Sedimentation by Water, Ward et al.[105], referring to that paper stated that, ". . . flocculating agents provide an economic solution to meeting water quality goals even on large surface mine areas. On three watersheds near Centralia, Washington, water quality was maintained within the new Federal limits for an estimated cost of $10/acre-ft of runoff." No indication is given as to what this cost includes or any of the other watershed factors which might influence cost. Regardless of this, one of the prime reasons

for not using coagulants given by the engineers questioned by the author was cost.

For coagulant use, mechanical and/or electrical equipment are necessary for feeding the chemical additives at the proper dosage rates. Whenever mechanical and electrical equipment is introduced to a system, maintenance requirement and costs increase.

Design criteria and chemical application methods or lack thereof are the other reasons proposed for coagulants not being widely accepted. A wide variety of chemical coagulants with varying degrees of effectiveness are commercially available. However, dosage rates for different sediment types at different concentration are not available. Even after the optimal dosage rate for a particular sediment type at a given concentration is determined, it must be remembered that in practice, sediment concentrations will vary with time throughout a runoff event. McCarthy[98] indicated that the turbidity fluctuation of the effluent from their preliminary pond was not sufficient to require a dosage rate change. However, since the flow rate did vary, the actual feed rate of the coagulant needed to be regulated to compensate for variations in flow rates. A method of monitoring the flow rate and regulating the chemical feed rate accordingly was developed, but an electrical power source was found to be absolutely necessary.

Other problems which may also need to be addressed, depending on specific site conditions are clear water source and temperature effects. If coagulants come in a solid form or concentrated liquid, a clear water source may be needed to dissolve or dilute the coagulant so as to be compatable with the feed system. Cold weather may require measures to prevent coagulants from freezing and/or dosage rates may need to be changed due to slower settling velocities caused by low temperatures.

It can be seen that many practical problems still exist in using coagulants to increase effluent quality. Although coagulants have been successfully used in at least three sediment basins in Washington State and at Lake Needwood in Maryland, their use has not gained wide acceptance throughout the rest of the country.

HIGH RATE SEDIMENTATION DEVICES

High rate sedimentation devices refer to inclined tube settlers which have been successfully employed in wastewater

treatment plants to reduce settling time. The only mention of their use in sediment ponds that was found in this study was in an EPA report titled, Joint Construction Sediment Control Project[66]. The report states, "Discussions with manufacturers of inclined tube settlers revealed that the removal efficiency of inclined tube settlers is greatly reduced at concentrations of less than 100mg/l. Consequently, the idea of installing such a device was abandoned since it would not economically add materially to the trap efficiency of the pond." The EPA[106] Process Design Manual for Suspended Solids Removal discusses at length the use of these tube settlers and similar devices in water and wastewater treatment plants.

CHAPTER V

MODELS

INTRODUCTION

The purpose of this chapter is to present the different types of computer models which have been developed and are available as design and analysis tools in sediment control. They can be divided into three basic groups: 1) hydrograph models, 2) sediment yield models, and 3) pond design models. This review of specific models does not attempt to cover all models that have been developed, but will be limited to a few models which, it is believed, give a fair representation of the current State of the Art. An extensive review and comparison of all existing models would be more of a determination of the State of the Art of numerical methods or computer models instead of sediment and erosion control. Thus, such a review was not conducted. The known principles and methods of sediment and erosion control have been presented in Chapters III and IV; this chapter merely shows the application of these principles in conjunction with digital computers. The detailed mechanics of the reviewed programs will not be given here. Instead, the uses, concepts, required input, limitations, and output will be presented. References will be provided for the reader desiring details on the actual use of the mentioned models.

HYDROGRAPH MODELS

Hydrograph models are used to process rainfall hyetographs through watersheds to obtain runoff hydrographs. As explained in Chapters II and IV, the hydrographs are necessary for the hydraulic design of sediment basins. These models are also used as integral parts of sediment yield models. Of the many hydrograph models which have been developed, four have been selected for presentation here. Each are applicable for small to medium size rural watersheds and thus can be used to model surface mined areas. The models to be reviewed are the following: 1) the Watershed Storm Hydrograph (WASH) Model, 2) the Ohio State University Version of the Stanford Streamflow Simulation Model, 3) the U.S. Department of Agricultural Hydeograph Laboratory-70 (USDAHL-70) Model, and 4) the Purdue Model.

The WASH Model

The WASH model, which is used as a subroutine in the DEPOSITS model, is presented by Ward et al.[34] in the DEPOSITS design manual. It simply computerizes the SCS method for determining time to peak and peak flow for a unit hydrograph. (The SCS method is described in detail by Haan and Barfield.[16]) The shape of the unit hydrograph is then determined by Haan's[97] equation,

$$\frac{q(t)}{q_p} = \left[\frac{t}{t_p} \; e^{1-t/t_p} \right]^{C_3 t_p} \qquad \text{EQ. 6}$$

Where: $q(t)$ = hydrograph ordinate at time t

q_p = peak flow rate

t_p = time to peak

c_3 = non physical parameter (see reference for equation and tabulated values)

The SCS triangular hydrograph method upon which this model is based was developed for watersheds of 2000 acres or less and thus is the size limitation for this model. Storms for which hydrographs can be generated are limited from 1 to 24 hour durations.

The WASH model requires the following input:

1) watershed drainage area in acres,
2) average watershed slope in percent,
3) watershed flow length in feet,
4) design storm duration in hours,
5) design storm rainfall in inches,
6) composite SCS curve number for the watershed,
7) correction factor due to impervious areas, and
8) correction factor due to channel improvements.

The SCS method is an empirical method and thus the model has the limitations associated with all empirical approaches. Results of the model, reported by Ward et al.[34], indicate that the model is fairly conservative, yielding

slightly higher peaks than those reported by the SCS in its manual SCS-TP-149 (1973).

The other three models to be reviewed differ from the WASH model in that they attempt to simulate the hydrologic cycle by using mathematical formulae to describe the known individual components of the cycle. Although not all of the following: precipitation, interception, evaporation, infiltration, transpiration depression storage, surface detention, interflow, groundwater flow, and overland flow.

O.S.U. Version of SWM

One of the earliest computer models developed to simulate watershed runoff by using mathematical formulas to describe the components of the hydrologic cycle was the Stanford Watershed Model (SWM). In this model, the watershed is divided into areas of equal flow time. That is, all of the runoff within a delinated area will drain during a given time increment. The time increment is usually 15 minutes. By measuring the area of these delineated sections, a time-area histogram is developed. Knowing the area of each time zone, the average runoff rate per time zone per increment of time can be calculated and a time-runoff diagram can be constructed for each time increment of the storm duration. Each of these time-runoff diagrams are lagged and then routed using a level pool routing technique to obtain the runoff hydrograph. This model considers the following components of the hydrologic cycle in determining runoff: precipitation, interception, infiltration, interflow, evapotranspiration and, if desired, snowmelt.

In 1974, Ricca et al.[110] at the Ohio State University (OSU) modified this model for use on smaller midwestern watersheds ranging in size from 1 to 50 square miles (2.58 to 129.5km^2). This was made possible by allowing the time increment to vary from 1 to 15 minutes. The model was further modified by adding a snowmelt subroutine for midwestern conditions, a swamp and soil crack storage rountine, and a routine to consider multiple recession constants.

This model requires the following input data:

1) precipitation,
2) evaporation,
3) soil surface moisture,
4) soil retention properties,

5) interflow storage and flow conditions,

6) groundwater storage and flow conditions, and

7) physical state and geomorphological properties of the basin.

The fundamental limitations of the SWM and all modified versions of it is that it is based on the "lumped" system concept. Although it does employ mathematical equations to simulate the different components of the hydrologic cycle, it lumps them all together without considering individual component's distribution spatially over the watershed or the interaction among components.

USDAHL-70

The United States Department of Agiculture (USDA) has developed several hydrologic models. One of the earlier ones, referred to as USDAHL-70, is described in detail in Technical Bulletin Number 1435, Agricultural Research Service, USDA. This model, like the SWM, uses mathematical equations to simulate the components of the hydrologic cycle. Each component is written as a separate subroutine to facilitate updating when improvements to component simulations are made. This program considers the following hydrologic processes: precipitation, infiltration, evapotranspiration, evaporation of soil moisture, subsurface flow, overland flow, and channel flow. The USDAHL model differs from the SWM type models in that the watershed is divided into three zones based on topography. The three topographic regions are uplands, characterized by mild slopes having moderate erosion, hillsides, having steeper slopes and susceptible to relatively severe erosion, and finally bottom lands, consisting of flat alluvium. For each zone, average values of soil characteristics are computed. Then infiltration, evapotranspiration and overland flow are calculated for each region individually and the runoff is routed from the upper zone through the lower zones to the channel system. This system reduces the "lumped" system effect in that it considers the distribution of the hydrologic components and their interaction to some extent. For example, infiltration rates will likely be higher in the uplands and bottom lands than on hillsides. Furthermore, the amount of infiltration which has already occurred in the bottom lands will determine how much of the runoff from the uplands and hillsides will be infiltrated or passed as overland flow as it is routed through the bottom lands. Although the lumped system is still basically applied within each region, the overall system more closely models conceptually the watershed than the previous lumped system models.

This model requires input data which is divided into four basic groups: 1) soil parameters and watershed zones, 2) flow routing parameters, 3) hydrologic parameters, and 4) crop and land parameters. The exact data required for each of these groups will depend upon which version of the model is selected. As mentioned earlier, the USDA has developed a series of these models each updating or refining the basic model.

Purdue Model

The final hydrologic model to be reviewed was reported by L.F. Huggines and E.J. Monke in Technical Report No. 1, Purdue University, Water Resources Center. This model, referred to as the Purdue Model was developed to simulate surface runoff hydrographs for ungaged watersheds ranging in size from 2 acres (8.09×10^{-3} km^2) to several hundred acres. This model uses a finite difference scheme and avoids the lumped system effects entirely by selecting elements sufficiently small such that significant hydrologic parameters can be assumed uniform throughout the element. Runoff is routed through one element to the next throughout the watershed. Flow from one element to the next is assumed to be perpendicular to the element boundary and in the direction of the steepest slope. The continuity equation is used to determine the runoff for each element. Hydrologic components simulated in this model include: precipitation, interception, infiltration and surface storage.

The four hydrologic models presented are a small sample of all the computer models available for generating runoff hydrographs. These models are not necessarily the latest, most comprehensive, accurate or widely accepted. No attempt has been made to compare and evaluate relative merits of all available models. The models selected were intended to show the different approaches which have been taken to utilize computers to obtain runoff hydrographs. The review included: an empirical approach consisting of computerizing the SCS method; a lumped system approach, utilizing mathematical equations to simulate individual hydrologic components; a "semi-lumped" system approach, which divides the watershed into three topographic regions; and a finite difference scheme approach, where elements are selected small enough to reasonably assume uniform hydrologic parameters throughout the element. The trend is definitely away from empirical approaches and towards simulation of individual hydrologic components and their interactions. Improvements are likely to be made in the area of formulating mathematical expressions which will more closely describe the physical phenomenon of the individual hydrologic components.

SEDIMENT YIELD MODELS

Before reviewing sediment yield models, brief mention will be made of a concept first developed by Meyer and Wischmeier[111] in 1969, and which has since been incorporated into many models. The first part of the concept stipulates that soil detachment is accomplished by either raindrop impact or overland flow, and that sediment transport is accomplished by raindrop splash or overland flow. Meyer and Wischmeier's concept then requires that the total amount of soil detachment be compared to the total capacity for sediment transport. If the total amount of soil detached is greater than the transport capacity, deposition will occur. The amount of deposition will be the difference between soil detached and transport capacity. If the capacity to transport sediment is greater than the amount of soil detached, then no deposition will occur, and the sediment yield will be equal to the amount of soil detached. This basic concept of detached soil available verses transport capacity is found in most sediment yield models.

Three sediment models have been selected for presentation here. These were developed by David and Beer, Onstad and Foster, and Simons et al.

David and Beer's Model

David and Beer[112, 115] developed their model at Iowa State University in 1974. It is a sheet and rill erosion model which uses the Kentucky Watershed Model (KWM), a modified version of the SWM, to simulate the hydrologic cycle. The simulated hydrologic cycle is used in determining sheet and rill erosion. However, recorded streamflow is read in as input for estimating channel bank erosion and bed scour. For sheet and rill erosion, an empirical equation is used to determine soil detachment and a power equation is used to calculate the transport capacity. For channel bank erosion and bed scour, a simple power function is used. The concept developed by Meyer and Wischmeier is then used to determine sediment yield and depostion. This model gives daily, monthly and annual suspended sediment loads.

Since this model is based upon the KWM, it has the same limitations as its hydrologic model. The most severe limitation is probably the fact that the KWM, like all versions of the SWM, uses the lumped system approach. Another major limitation of the model as a whole, is that it requires daily observed streamflow values as input for stream erosion

estimation. In spite of these limitations, the model's developers report favorable results when they tested it on the Four Mile Creek Watershed near Tracer, Iowa.

Onstad and Foster's Model

Onstad and Foster[113] developed their erosion model in 1974 to determine sediment yield and total runoff for single storms on a watershed. The model uses the USDAHL-73 model to simulate the hydrologic cycle, and therefore, the watershed is divided into the three topographic regions as mentioned above in the section describing USDAHL models.

Onstad and Foster use the USLE as modified by Foster et al.[114] to determine the amount of soil detached. An empirical equation using basically the same factors found in the USLE is used to compute transport capacity. These factors are assumed to be uniform within each delineated region. Erosion and deposition is then calculated for each zone, based on the concept presented by Meyer and Wischmeier[111], as the runoff and sediment is routed from the higher zones through the lower zones into the channel. All calculations are first made on a unit width basis and then applied to the entire watershed.

The main advantage of this type of an approach is that it tends to minimize the lumped system effects by dividing the watershed into areas having somewhat similar hydrologic parameters. Results of this particular model are limited and not in suitable form to accurately judge its capabilities.

Simons' Model

The final sediment yield model to be reviewed was described by Li et al.[116] in 1976. The model itself was developed by Simons et al. in 1975. In this model, overland flow is separated from channel flow. The overland flow portion of the model considers interception, infiltration, overland routing of water to the channel system, subsurface routing of water to the channel and sediment routing to the channel. The channel flow portion of the model routes water and sediment delivered to the channel from the overland flow areas and computes degradation and aggradation in the channel.

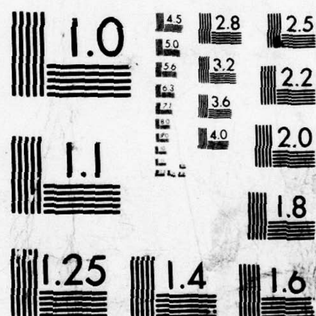
Soil detachment by raindrop impact is calculated using a power function of the rainfall intensity, while detachment by flow is assumed to be a function of the local bed shear stress. A distinction is made between bed load and wash

AD-A077 709 ARMY MILITARY PERSONNEL CENTER ALEXANDRIA VA F/G 8/9
THE STATE OF THE ART OF EROSION AND SEDIMENT CONTROL FOR SURFAC--ETC(U
NOV 79 J L GILBREATH

UNCLASSIFIED NL

2 OF 2
AD
A077709

END
DATE
FILMED
1-80
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

load tranport capacities. The transport capacity for bed load material is assumed to be a function of the local effective shear stress and the Meyer-Peter-Miller bed load equation. The wash load transport rate is assumed to be a function of bed shear stress and available loose soil.

Both water and sediment are routed using the continuity equation and a finite difference scheme. Thus, the lumped system approach is avoided completely. This model provides runoff hydrographs and sediment graphs for individual storms on small watersheds.

Li et al.[116] report that the model was tested on two watersheds and that the synthesized values compared satisfactorily with observed values for the peak flow, time to peak, water yield, and sediment yield.

There are many other sediment yield predicting models besides the three reviewed here. These three models were selected merely to demonstrate different approaches which have been taken to utilize computers in predicting sediment yield. Their approaches parallel the type of approaches used in the later three hydrologic models. That is, a model which minimizes the effect of a lumped system approach by dividing the watershed into three topographic regions, and finally a finite difference model which eliminates the lumped system approach by dividing the watershed into elements small enouth so that hydrologic parameters can reasonably be assumed to be uniform across the element.

POND DESIGN MODELS

The final two models to be reviewed are classified as pond design models. These models are basically used as an aid to determine optimum spillway elevations, riser diameters, embankment heights and detention times.

Nesbitt and Notary's Model

The first model to be reviewed was presented by Nesbitt and Notary[97] at the Federal Surface Mining Regulations Conference in 1979. This model is basically a combination of a hydrologic model and a computerized routing technique to determine the detention time, embankment height and spillway pipe length. Watershed parameters are read in and an inflow hydrograph for a 10-year, 24-hour rainfall is generated. The stage-volume data for the proposed dam site is then read and a trial riser diameter, riser elevation and spillway pipe

length are assumed. The generated hydrograph is then routed through the pond and the flood crest elevation and detention time are calculated. If the detention time does not meet OSM requirements (24 hours) a new riser size and/or crest elevation are selected and the process is repeated until the optimum riser diameter and elevation are found. Next, a design storm is routed through both the principal and emergency spillways to determine the final height of the embankment. A 25-year, 24-hour design storm is used for embankments less than 20ft. (6.1m), and a 100-year, 24-hour design storm is used for embankments greater than 20ft. (6.1m). Finally, the assumed spillway pipe length is checked against the required length which can now be determined since the flood crest elevation and consequently dam height is known. If necessary, the assumed pipe length is corrected and the process is repeated until the assumed pipe length is within 10% of the required.

This model employs no new principles, but combines tools and methods discussed earlier to reduce the iterative work required to find the optimum riser size and elevation.

DEPOSITS Model

The final model to be discussed was developed by Ward et al.[34] and is called the DEPOSITS (DEposition Performance Of Sediment In Trap Structures) Model. It ". . . is a conceptual model which describes the sediment transport and deposition process in a reservoir as a function of the basin geometry, inflow hydrograph, the inflow sediment graph, the sediment characteristics, the outlet spillway design and the hydraulic behavior of the flow within the basin."[34]

This model can be used to predict trap efficiency, storage reduction due to sediment deposits, and effluent suspended sediment concentrations. Thus, this model does not actually aid in selecting optimum design specifications, but predicts the results of design proposals. To accomplish this, the WASH model is used as a subroutine to generate the pond inflow hydrograph which is then plug flow routed through the pond.

In order to route the runoff and sediment hydrograph through the pond, the model requires several pieces of input data which include: the sediment storage requirement, total storage volume, stage-storage data, and the principal and emergency spillway specifications. Although the model does not attempt to simulate the flow hydraulics within the basin, control variables are used to adjust for such things

as the plug flow assumption, short-circuiting, dead space, inflow and outflow conditions and the use of chemical flucculants. The model does not calculate or predict sediment yield. It is necessary therefore to input a sediment inflow graph or the total sediment mass entering the basin during the storm event. If the latter approach is used, the model will distribute the total sediment load throughout the runoff event, proportioning it according to the flow rate.

Ward et al.[34] have tested this model on eleven basins throughout the nation, and were able to explain over 90% of the variation in trap efficiency.

Both the DEPOSITS Model and Nesbitt's model can be used as an aid in sediment pond design, but both use a different approach. Basically, Nesbitt's model will select the principal spillway riser diameter and elevation, and give the final embankment height all based on a required detention time. The DEPOSITS Model on the other hand will predict the efficiency of a given pond design.

In summary, this chapter has reviewed various computer models which have been developed for design and analysis work in sediment and erosion control. An attempt has been made to present the different areas in which computer models can be of use, and some of the different procedural approaches which have been developed.

CHAPTER VI

SUMMARY AND RECOMMENDATIONS

INTRODUCTION

The purpose of this chapter is to summarize the State of the Art of erosion and sediment control. Material presented in Chapters II through V will be summarized and displayed in tabular form. Next, a list of known on going research is listed. Finally, conclusions, needed research and recommendations are presented.

SUMMARY

In an attempt to concisely display this information, four tables were constructed with basically the same format. Table 6 summarizes methods and techniques of predicting and quantifing sediment characteristics, rates, and concentrations which are important in the study of erosion and sediment. The table is divided into four columns headed: Item, Summary, Comments, and References and Sources of Additional Information. Comments and references are listed horizontally across from the statement in the summary column to which they apply. The reference will be listed horizontally across from the item listed if it applies generally to the item, and not specically to any statement in the summary column. The last column will contain all references found in the text of this thesis that are related to the particular item as well as any reference which was found on the subject, but which has not previously been mentioned. When applicable, concluding remarks about the State of the Art for the particular item, will follow the last statement in the summary column and run the width of the table.

Table 7 summarizes the material presented in Chapter III. The table has two sections. The first summarizes erosion control, and the second summarizes sediment control. The format is similar to Table 6 with the exception of the first two columns. For the erosion control section, the first column delineates the specific erosion processes, and the second column lists the methods or techniques of control for each of the erosion processes. In the sediment control section, the first column lists the control processes, and

the second column lists the specific control methods.

Table 8 summarizes the considerations for sediment pond design. Following the format of the other tables, the first column lists the specific design item and the second column summarizes the design considerations.

Table 9 summarizes the computer models which were reviewed. The first column lists the type of model and the second column gives the particular models which were reviewed. The rest of the table follows the same format as the previous three tables.

Table 6. Summary of Methods and Techniques to Describe and Predict Sediment Characteristics, Concentrations, and Rates

ITEM	SUMMARY	COMMENTS	REFERENCES AND SOURCES OF ADDITIONAL INFORMATION
Particle Size Distribution	1. Purpose and Characteristics		34
	(a) Size distributions are used to determine what percent of the suspended load can be removed by settling.		
	(b) Particle size distribution of eroded sediment is different from the particle size distribution of soil from which the sediment is eroded.		1, 30
	(c) The particle size distribution varies throughout the runoff event.		108
	(d) Young and Onstad's method of predicting particle size distribution was the only prediction method found in the literature.		29, 30
	Sediment size distributions are required if the percent of the suspended solids to be removed by settling is to be predicted. It is a difficult task to take sediment samples and to physically measure size distributions without breaking down the aggregate particles. Only one method has been found in this study which is capable of predicting sediment particle size distributions, and that method does not address the variation of the distribution with time throughout a runoff event.		
Sediment Graphs	1. Characteristics		
	(a) Time rates of sediment loads	Four methods have been found in the literature: Renard and Laursen; Bruce et al.; Prendon-Herrero, and Williams	20, 21, 22, 23
	(b) Product of hydrograph and sediment concentrations		
	(c) Concentrations vary with time throughout the runoff event at a different rate than the flow		19
	Although sediment graphs are important in determining peak sediment loads, little information is presently available on how to obtain them. Of the four methods referenced here, two have not been extensively tested, and the other two methods are only applicable to gaged watersheds.		
Methods of Predicting Sediment Yield			45, 46, 47, 48, 51
	1. Universal Soil Loss Equation (USLE)	Only two specific methods to predict sediment yield are reviewed in detail in this thesis, the USLE and the MUSLE. These methods appear to be the most applicable and most widely used for surface mined areas.	16, 40, 42, 49, 52, 53, 54
	(a) Empirical equation, developed in English units to predict sheet and rill erosion.	The equation can be converted to the metric system, but tables for the values of the various factors are not readily available.	40
	(b) Predicts gross erosion - requires a delivery ratio to determine yield if frequent opportunity exists for deposition.		
	(c) Composed of four factors: i) rainfall factor, R ii) erodibility factor, K iii) length/slope factor, LS, and iv) control practice factor, CP		
	(d) Used to predict annual erosion rates.	It has been used to predict soil loss on a single storm basis with limited success. It is recommended that the USLE be used solely for predicting annual rates.	

Table 6. (continued)

ITEM	SUMMARY	COMMENTS	REFERENCES AND SOURCES OF ADDITIONAL INFORMATION
Methods of Predicting Sediment Yield	2. Modified Universal Soil Loss Equation (MUSLE)		55, 56
	(a) Replaces the USLE's rainfall factor with a runoff factor.		
	(b) Eliminates the need for a delivery ratio.		
	(c) Used for daily, monthly or yearly sediment yield.		
	3. Chukwuma's Modified Rainfall Factor for Use in the USLE		109
	(a) Has only received limited testing.		
	(b) Indications from initial testing is that predictions for single storm events are improved.		
	The USLE is applicable for small to medium size watersheds as would be found in surface mined areas. It has received wide acceptance in the agricultural, construction and mining fields. Presently, in the mining industry, it is used to predict annual sediment yield for use in sizing sediment ponds. A method for predicting sediment yield on a single storm basis is desired in order to evaluate the effectiveness of upstream control measures. The modified versions of the USLE by Williams and Chukwuma appear to be providing good predictions for single storms, but more testing is required of both methods.		
Measurement of Suspended Solids Concentrations	1. Methods of Obtaining Water Samples for Laboratory Analysis of SS Concentrations		
	(a) Sample is extracted as water passes over the weir or spillway.	These methods do not disturb the hydraulics of the streamflow when extracting samples.	
	i) splitter samplers		58
	ii) fractional water sediment sampler		59
	iii) Coshocton wheel	This method does not operate properly for heavy loads of coarse sediment. Modifications have been applied but then, the percent of fine and coarse sediment sampled varies with concentrations and flow rates.	60, 61
	iv) rotating arm sampler	Variations in percent of sampled flow with changes in flow rates have been reported.	62, 107
	(b) Sample is withdrawn directly from stream.		
	i) integrating samplers		
	a) point integrating	This method does not allow for concentration variations in the stream cross section.	36
	b) depth integrating	This method does not allow for concentration fluctuations with time.	64, 36
	ii) instantaneous samplers	Does not allow for either spatial variations or temporal fluctuations.	63
	iii) pumping samplers	Samples are not isokinetically collected. Representative samples of coarse sediment are not obtained. A power source is required.	36
	iv) special samplers	These samplers are installed to collect one sample at a predetermined stage. They have the same disadvantages of instantaneous samplers.	36, 64, 65

Table 6. (continued)

ITEM	SUMMARY	COMMENTS	REFERENCES AND SOURCES OF ADDITIONAL INFORMATION
Measurement of Suspended Solids Concentrations	2. <u>Measuring Suspended Solids Concentrations without Collecting Water Samples</u> Methods of Measurement (a) Turbidity meters (b) Electronic sensing methods (c) Ultrasonic methods (d) Nuclear methods	Very little has been found in the literature on the usage of these methods. Some work has been reported on the use of turbidity meters.	36, 64, 65, 133
	Although many methods for measuring SS concentrations have been developed, of the water sampling type only the splitter samplers and fractional water-sediment samplers appear to provide representative samples. Of the methods not requiring water sample collection, to the author's knowledge, only turbidity meters are at an operational point of development. And it appears to the author that turbidity meters will have the same difficulty experienced by point integrating samplers in obtaining representative measurements of SS concentrations.		

Table 7. Summary of the State of the Art of Erosion and Sediment Control

SECTION 1 - EROSION CONTROL

EROSION PROCESS	METHODS/TECHNIQUE OF CONTROL	COMMENTS	REFERENCES AND SOURCES OF ADDITIONAL INFORMATION
A. Control Soil Detachment for Interrill Erosion			
1. Detachment by raindrop impact	Protect or shield soil by using vegetation and/or mulches to absorb kinetic energy:		
	- mulches, netting, and methods of anchoring		49, 69, 70, 71, 72
	- vegetation and revegetation practices		49, 69, 70, 71, 72, 73, 74, 75, 76
	Strengthen or stabilize soil to withstand kinetic energy of raindrops:		
	- chemical binders, mulches, and tacks		49, 69, 70, 71, 77
2. Detachment by shear due to overland flow			
(a) Prevent runoff from entering disturbed area	Collect and divert runoff with interceptor dikes or diversion ditches		16, 49, 69, 70, 71, 72
(b) Reduce runoff's effect			
i) reduce runoff volume	Increase infiltration by using vegetation	Vegetation root systems increase infiltration by increasing soil permeability. Additionally, foliage prevents the surface from being sealed by raindrop impact.	49, 69, 70, 71, 72, 73, 74, 75, 76, 78
ii) reduce runoff velocity	Vegetate surface to retard flow		49, 69, 70, 71, 72, 73, 74, 75, 76, 78
	Reduce slope by regrading		12, 80, 116
	Reduce slope length by using diversion ditches and contour trenching.	Contour trenching also increases infiltration	16, 81
B. Control Soil Detachment for Rill and Channel Erosion			
1. Prevent the occurrence of rills and gullies	Distribute flow and reduce velocities with level spreaders		49
	Prevent soil particle movement with erosion checks	Erosion checks allow passage of subsurface flows but prevent movement of soil particles. These are used in swales, ditches and on critical slopes.	49, 70, 71
2. Prevent degradation of channel banks and beds			
(a) reduce velocity of	Use grade control structures such as check dams to reduce hydraulic gradients		49, 69, 70, 71, 72
	Dissipate energy by using obstructions such as baffles and/or using rough channel linings		49, 70, 71, 72
(b) protect channel	Protect channel by lining with vegetation, gabions, riprap, concrete, asphalt, etc.	Chutes and flumes used to transport water down the face of a slope need to be lined also.	49, 69, 70, 71, 72

Table 7. (continued)

EROSION PROCESS	METHODS/TECHNIQUE OF CONTROL	COMMENTS	REFERENCES AND SOURCES OF ADDITIONAL INFORMATION
C. Control Soil Transport			
1. Transport by raindrop splash	Reduce steepness of slope by regrading		12, 18, 80, 116
2. Transport by runoff flow	The methods mentioned above that reduce runoff volume by diversion or infiltration, or reduce velocities by reduction of hydraulic gradients or dissipation of energy, will serve also to control the transport process.		

SECTION 2 - SEDIMENT CONTROL

PROCESSES TO CONTROL SEDIMENT	METHOD/TECHNIQUE	COMMENTS	REFERENCES AND SOURCES OF ADDITIONAL INFORMATION
A. Settling	Sediment traps created by check dams, sandbag or straw bale barriers, log and pole structures, or excavated pits will cause settling.	Only large particles will be removed by sediment traps. For more efficient sediment removal, sediment ponds are required.	27, 49, 69, 70, 71, 72
B. Filtering	Filter berms, straw bales, silt fences and vegetative filters are available means of filtering sediment.		49, 70, 71, 27, 85, 86, 87, 88, 89

Table 8. Summary of Sediment Pond Design Considerations

ITEM	DESIGN CONSIDERATIONS	COMMENTS	REFERENCES AND SOURCES OF ADDITIONAL INFORMATION
Pond Size			14, 37, 94, 95, 96
	1. Hydraulic Loading (OSM Requirements)		
	(a) Must safely pass 10-yr., 24-hr. storm through the principal spillway only.	Routing techniques to assure that the hydraulic loading requirements are met are well established and have been discussed in Chapter II.	14
	(b) For dams 20 ft. (2.09 m) high or less and impounding 20 ac-ft. (1233.5 m^3) or less, the combined discharge rate of the principal and emergency spillways must be sufficient to safely pass a 25-yr., 24-hr. storm.		
	(c) For dams exceeding the height and/or impoundment limits mentioned in 1(b) above, the combined discharge rate of the principal and emergency spillways must be sufficient to safely pass a 100-yr., 24-hr. storm.		
	2. Sediment Storage (OSM Requirements)		14
	(a) Accumulative sediment volume from drainage area for a minimum of 3 yr. or	Annual sediment yield is to be determined by the USLE.	
	(b) .1 ac-ft. for each ac (304.75 m^3/ha) of disturbed area or		
	(c) .035 ac-ft for each ac (106.67 m^3/ha) of disturbed area if operator demonstrates that sediment removal by other methods equals the reduction of sediment storage volume.		
	3. Detention Time (OSM Requirements)		14
	(a) Defined as time difference between the centroids of the inflow and outflow hydrographs.	Detention time as defined here is not an accurate indicator of pond efficiency.	97
	(b) 24-hr. detention time is required for 10 yr. - 24 hr. precipitation events.	The only exception to the detention time requirement is if the operator can demonstrate that OSM effluent standards are met.	
	4. Surface Area	There are no OSM requirements for surface area. Although Hazen has shown that surface area is one of the most important factors in determining pond efficiency, it is rarely used as a design criterion in practice.	27, 37, 117
	(a) Required surface area is based on the surface loading rate (or the flow through velocity divided by the critical settling velocity).	The surface loading rate assumes ideal settling.	
	(b) EPA suggests a correction factor of 1.2 be applied to the surface area, calculated from the surface loading rate, to adjust for non-ideal settling.		69
	(c) Skelly and Loy recommend correction factors based on pond shape.		27
	No adequate method or design criteria is available for determining pond size requirements to assure sufficient time for sediment settling. The surface loading rate method was developed for permanent uniform basins like those found in treatment plants. Detention time, as defined here, can be misleading when used as a trap efficiency indicator. Irregular shapes of ponds, non-uniform depths, fluctuating flow rates, and fluctuating sediment concentrations, all characteristics of surface mine sediment ponds, have thus far hindered the development of an acceptable means for sizing ponds.		

Table 8. (continued)

ITEM	DESIGN CONSIDERATIONS	COMMENTS	REFERENCES AND SOURCES OF ADDITIONAL INFORMATION
Ponds in Series	Reasons for Use (a) Used when topograph will not permit single large ponds. (b) Used to increase detention time, although the method for calculating detention time for settling velocity purposes is not established. (c) Smaller ponds can be used in series with primary pond to remove larger particles before they enter the primary pond. (d) Smaller ponds in series may be used instead of a larger one to facilitate cleaning and to reduce construction and removal costs. (e) Used when chemical coagulants are employed.		37, 69 98, 117, 118
	No requirements exist for use of ponds in series, and nothing has been found in the literature to indicate that ponds in series will produce higher quality effluent than single large ponds if all other factors are equal. Construction, cleaning and removal costs may favor smaller ponds in series, but this must be determined on a site specific basis. The present method of employing chemical coagulants requires that at least two ponds be used in series.		
Pond Shape	1. Length/Width Ratio (a) Used as an indicator of possible short circuiting. (b) For irregular shaped ponds, the effective width is equal to the surface area divided by the effective length (or the actual length of the flow path). (c) Baffles can be used to increase effective flow length. (d) Recommended values range from 2:1 to 5:1.		27, 95, 72, 94, 69, 99
	2. Geometric Shape of Pond (a) Sediment ponds have been reported with the following shapes: circular, rectangular, triangular and irregular. (b) Skelly and Loy indicate that pond shape affects short circuiting and provides adjustment factors for surface loading rates based on pond shape.		27, 37, 100, 101 27
	Most sediment ponds reported in the literature are irregular in shape, taking their shape from the existing topography. There appears to be no concensus on the best geometric shape for providing the best hydraulic flow conditions for sediment removal. Length/width ratios are used as indicators of a pond's susceptibility to short circuiting. Ratio values are recommended by different agencies, but no specific one is required by OSM.		

Table 8. (continued)

ITEM	DESIGN CONSIDERATIONS	COMMENTS	REFERENCES AND SOURCES OF ADDITIONAL INFORMATION
Inlet Design	Principal Functions		
	(a) Dissipate energy to reduce velocities and turbulence and thus cause deposition; to accomplish this, obstructions are placed in the flow path in the following form: i) dumped rocks ii) log and pole structures iii) check dams iv) baffles		27, 37, 96
	(b) Distribute flow across the pond width to increase the effective cross-sectional area which reduces velocities and increases detention time; it also decreases short circuiting; methods include: i) apron inlets ii) baffles iii) multiple inlets		27
	(c) Filter influent to remove large particles before entering the pond, two methods are available: i) straw bales ii) silt fences		27
Outlet Design	1. Principal Spillway		14, 16, 27, 69, 102
	(a) Size requirements by OSM regulations		14
	i) capable of safely passing 10 yr.-24 hr. storm without emergency spillway;		
	ii) must provide 24 hr. detention time for 10 yr.-24 hr. storm.		
	(b) Location considerations		27, 69
	i) provide a maximum travel distance from inlet;		
	ii) minimum short circuiting and dead space.		
	(c) Types		27, 69
	i) standard riser pipe with trash rack and antivortex defice with or without perforations;		70, 96, 99, 103, 104
	ii) troughs and skimming weirs;		27, 69, 100, 104
	iii) lined channel spillways.		49, 69, 70, 72
	2. Dewatering		34, 37, 96
	(a) Used to lower pond level to provide more storage for next runoff event.		
	(b) Desirable to minimize dewatering for two reasons:		34
	i) poor quality water is usually withdrawn;		
	ii) permanent pools are desirable because they increase detention time and help prevent scour caused by inflow velocities.		

Table 8. (continued)

ITEM	DESIGN CONSIDERATIONS	COMMENTS: Advantages	COMMENTS: Disadvantages	REFERENCES AND SOURCES OF ADDITIONAL INFORMATION
Outlet Design	(c) Types of dewatering devices			
	i) single or multiole perforated risers	No operator required	Poor quality effluent; No base flow storage	27, 69
	ii) siphon drawdowns	No operator required; Provides some base flow storage	Poor quality effluent; Water is always withdrawn below surface	27, 37, 69
	iii) manual	Good quality effluent - water is withdrawn only when clear	Operator required	34, 96
	iv) subsurface drains	No operator required; Good quality effluent	Easily clogged; Expensive to install	27, 69
	3. <u>Filters</u>			95
	(a) Filters around perforated risers have been tried but have been found to clog too easily.			
	(b) Commercially manufactured fiberglass (skimming weir) filters are available for use in conjunction with discharge troughs.	The effectiveness of these filters for sediment ponds is unknown.		
	4. <u>Emergency Spillways</u>			
	(a) Combined principal and emergency spillways must be capable of safely passing a design storm specified by OSM.	Design storms specified by OSM all shown above under Pond Size Design Considerations.		[illegible]
	(b) Normally consists of a lined channel.			49, 69, 70, 72
	Permanent pools are desirable in that they increase detention time and protect the deposited sediment from resuspension by the influent. However, no quantitative studies have been found which indicate the optimum size of the permanent pool or its quantitative relationship with effluent quality. An ideal dewatering method is not presently available. The one method which provides good quality effluent requires an operator. Filters used with outlet structures have been unsuccessful due to clogging. A tank filter which has been used in septic tanks successfully for 15 years has recently been used in sediment ponds. No reports on its effectiveness in sediment ponds have been found.			
Baffles	1. <u>Uses</u>			27, 34, 69
	(a) Dissipate energy			
	(b) Distribute flow evenly across pond			
	(c) Direct flow			
	2. <u>Types</u>			27, 34, 69
	(a) Log and pole			
	(b) Rough sawed lumber or exterior plywood			
	(c) Impermeable plastic brattice cloth			104

Table 8. (continued)

ITEM	DESIGN CONSIDERATIONS	COMMENTS	REFERENCES AND SOURCES OF ADDITIONAL INFORMATION
Flocculation/ Coagulation	<u>Use of Coagulants</u> (a) Used to aid in removal of colloidal suspensions (b) Requires laboratory test to determine the best coagulant and dosage rates (c) Requires rapid mixing of chemicals, followed by slow mixing, and finally quiescent settling (d) Two ponds are required in this process		98, 118, 117
	No study has been found which shows the effectiveness of specific coagulants for removing given types of sediments. Each site requires laboratory tests to determine the best coagulant and its dosage rate. Application rates vary with flow rates, sediment concentrations and temperature. Methods of handling these varying application rates need to be developed which are practical, reliable and economic. Although it is a widely accepted opinion that coagulation is required to meet effluent standards in areas having high clay contents, the method has not received wide use. The author feels that the primary reasons are expense and lack of know-how.		
High Rate Sedimentation Devices	<u>Inclined Settlers</u>	No reports have been found describing the use of inclined settlers for anything other than treatment plants.	66, 106

Table 9. Summary of Reviewed Models

TYPE	NAME	COMMENTS	REFERENCES
Hydrograph Models	WASH Model	Empirical model	34
	O.S.U. Version	Mathematical equations simulate hydrologic processes Lumped system approach	110
	USDAHL-70	Mathematical equations simulate hydrologic processes Semi-lumped system approach	130
	Purdue Model	Finite difference model	131
Sediment Yield Models	David and Beer's Model	Uses KWM hydrologic model Lumped system approach	112, 115
	Onstad and Foster's Model	Uses USDAHL-73 hydrologic model Semi-lumped system approach	113
	Simons' Model	Finite difference model	116
Pond Design Models	Nesbitt and Notary's Model	Combines hydrologic model and computerized routing technique Selects optimum riser and pipe size based on a required detension time	132
	DEPOSITS Model	Empirical model Uses WASH hydrologic model Predicts pond performance	34

CURRENT RESEARCH

The known current research listed below is a by-product of the main investigative work of this study. As it was not the main objective of this thesis, an exhaustive search was not conducted solely for its completion. It therefore should not be considered as comprehensive.

The Federal EPA[124] in Cincinnati reports current research in the following areas:

1. Demonstration of the effectiveness of the modified block-cut method of surface mining in providing on-site control of sedimentation

2. Evaluate the effectiveness of head-of-hollow fill and mountain top removal mining methods in reducing erosion and landslides

3. Determination of the feasibility of using a vegetative filter zone to assist in controlling fine-grained sediments originating from surface mining activities

4. Demonstrations of the best methods of preventing erosion from haul road construction areas

5. Demonstration of the value of fly ash to improve soil conditions and vegetative growth on surface mined land

6. Demonstration of effectiveness of debris basins to control sediment discharges for surface mining operations in steep slope terrain

7. Development of aquatic grasses in ponds to improve the suspended sediment removal efficiency of the pond

8. Development of a mathematical model to predict water quality of surface and subsurface runoff on surface mine spoils in the Rocky Mountain Region

Vogel[125] reports the following current research being conducted at the School of Forestry at the University of Kentucky:

1. Determination of the feasibility and economics of using waste products from sawmills and other wood processing plants for mulch and amendments on

surface-mine spoils

2. Evaluation of the effects of different mulches and application techniques on the survival and growth of tree seedlings

Davis et al.[126] reported in 1977 the following current research being conducted by the Montgomery County Department of Environmental Protection (MCDEP) in Maryland.

Development of the following relationships:

1. Sediment loads flowing into a basin
   vs. percent exposed tributary area
   vs. rainfall (incremental and peak intensity, and storm volume)
   vs. runoff (peak flow and volume)
   vs. soil type and texture
   vs. average land slope (percent and length of slope)

2. Rainfall intensity vs. peak sediment load

3. Total sediment load measured vs. predicted using USLE

The Bureau of Mines[129] is conducting research on the hydrology and water quality of watersheds subjected to surface mining. Two objectives of their study are:

1. Develop or adapt a ground-water model for simulations of ground-water flow conditions and movement of solutes for the pre- and post-surface mining conditions

2. Develop or modify a computer model for simulation of the hydrologic and water quality regimes of the study watersheds for both pre- and post- surface mined conditions

Robinson and Meyer[119] reported in 1976 the following research areas, and where the work is currently underway. This list is taken directly from Robinson and Meyer's report.

1. Improve erosion prediction relationships for steep, flat, and long slopes using concepts derived from model, laboratory, and field data (Oxford, Lafayette)

2. Determine factor values for new or existing practices not yet evaluated for the USLE (Lafayette, Columbia, Oxford, Pullman)

3. Study the characteristics of rainfall and runoff that affect soil erosion rates, especially in the Southeast, Southwest, and Northwest, where R factor values in the USLE are unsatisfactory or unknown (Oxford, Pullman, Tucson)

4. Evaluate soil erodibility characteristics of major agricultural, construction site, and surface-mine soils, subsoils, and mixed soils and correlate these characteristics with readily obtainable physical, chemical, and spectral parameters and with relative susceptibility to rill and interrill erosion (Oxford; Watkinsville; Lafayette; Coshocton, Ohio; Columbia; Morris, Minnesota; Pullman; University Park, Pennsylvania)

5. Adapt the USLE for construction, mining and urban conditions and evaluate the equation's factors for these conditions (Lafayette, Oxford, University Park, Coshocton)

6. Conduct basic research to study erosion deposition processes to serve as foundation for developing new applied erosion models (Lafayette, Cloumbia, Oxford)

7. Develop new erosion equations to replace the USLE, based on mechanics of erosion concepts, such as separation of rill and interrill erosion (Lafayette, Columbia, Oxford)

8. Study erosion processes and erosion control systems for land where erosion results primarily from rainfall and snowmelt on frozen soils (Pullman)

9. Explore the potential for decreasing erosion by topographic modification and mulching on roadsides, mine spoil, and other massive landforming situations (Oxford, Lafayette, Coshocton)

Wu and Bedford[129] at The Ohio State University are developing a rational model of the erosion process that can account for the input variables of rainfall, soil properties and topography as statistical quantities.

CONCLUSIONS

The following are the conclusions drawn by the author about the State of the Art of sediment control. A few general comments will be made first, followed by more specific statements about the individual topics covered in this report.

The motivation behind the research for improvements in erosion and sediment control for surface mined areas is the high effluent requirements set by OSM. Many operators, however, feel that there is no logical basis for the OSM effluent standards and that they are arbitrarily applied across the country with no regard for the differences of hydrologic conditions, topography, soil type or quality of receiving waters. Many cases are reported where the receiving waters have higher SS concentrations than OSM will allow mine operators to discharge.

The purpose of this study was not to determine the applicability of the Federal regulations. These comments have been presented merely to provide the reader with a perspective of the situation. The author has received the distinct impression that in the coal industry, in general, there is a greater demand for changing the effluent requirements than there is for developing means to meet them.

The current State of the Art of sediment control, as practiced, is not capable of meeting effluent requirements during and after design storm events if clay is present in the sediment. Pilot control programs in certain parts of the country, however, have been able to meet the requirements by using coagulation.

The following conclusions will address subject areas in the order of presentation in Chapters II, III, IV, and V. The hydrologic and hydraulic tools are sufficiently well developed to meet their requirements in the current methods of designing control measures. However, two areas requiring more research if design techniques are to be refined are as follows: 1) the hydraulics and sediment transport through non-submerged vegetative filters, and 2) hydraulics and sediment deposition, resuspension, and transport in sediment ponds.

Sediment classification is not nearly as well defined as soil classification. More work will be required in this area if predictions of particle size distributions are to be made. Refinements in this area would also be an aid in determining the sources of sediment and consequently an aid in determining effectiveness of control measures.

Sediment graphs, which portray the time rate of sediment load, have not received much use. Few reports have been found on the subject. Perhaps the importance of such a tool needs to be examined first. Peak SS concentrations appear to be sufficient for designing ponds without chemical coagulants. If however, coagulants are to be used, a complete time history of the sediment load will aid in determining required ranges of chemical coagulant application rates.

Many means of sampling water to determine SS concentrations have been developed. However, only two methods were found in which samples appear to be representative of the entire flow cross section. Both of these require drop structures.A reliable method of obtaining representative water samples without a drop structure or a means of determining representative SS concentrations without taking water samples is needed. Many studies report findings of observed effluent qualities, but fail to mention the method used to measure the sediment concentrations. Standardization in this area is required if studies are to be correlated.

In the area of sediment yield prediction, much work has been done. Satisfactory results are being reported in obtaining good predictions of yields on an annual, monthly and single storm basis by using the USLE or one of its modifications. The main drawback on these methods are that they are empirical, and much data is still required for their successful use on surface mined areas. These methods seem to be capable of meeting the present demand for accuracy of sediment prediction. However, there are a few who claim a need for a more physically based prediction equation.

Qualitatively the erosion process is well defined, and the principles for its control are understood and being applied. Difficulty does exist however, in quantifying the erosion processes and the effectiveness of the control measures.

There is a great deal of effort presently directed at determining the best methods of revegetating disturbed land. Proper revegetation will of course solve the long range problem of erosion of surface mined land; however, the problem will still exist on all disturbed land until a proper vegetative cover is restored. In the mean time, other erosion and sediment control measures need to be applied.

There are basically two sediment control processes, filtration and settling. Filtration has not received much success except in areas of small flows. The process itself, for removing fine particles, is too slow.

Settling has been done on a small scale by using sediment traps and on a large scale with sediment ponds. Removal of large particles, generally found in bed load material, is no problem and can easily be handled with sediment traps. As the particles decrease in size, the difficulty of removal increases. Particles of colloidal size, are for practical purposes, impossible to remove without the use of chemical coagulants. However, very few ponds include chemical treatment in their design even though the sediment contains clay, which is not being removed. The reason for not using chemical coagulants appears to be its expense and the lack of established methods and procedures for determining application rates, and for adjusting them for fluctuations in flow rates and sediment concentrations.

Qualitatively, the factors involving pond efficiency have been defined; however, many are not well defined quantitatively. Exact relationships between pond efficiency and permanent pool size, length/width ratio and the geometric shape of the pond still defy definition.

Outlet structures and dewatering devices in most cases are not designed in accordance with established principles. For example, it is known that there exists a certain minimum detention or settling time required for particles of a given size to settle out. Also, it is an accepted principle that, barring algae growth, the highest quality of water will be at the surface of the pond. In spite of these principles, many outlet designs withdraw water with little or no settling time and/or remove the lower quality subsurface water.

The difficulty in defining and quantifying design criteria for sediment ponds is due to the irregularities in pond shapes and depths, and the non-uniform, unsteady hydraulic conditions which exist. Perhaps computer models, using finite difference or finite element schemes, could be used to simulate and explain the hydraulic and transport phenomenon within the sediment ponds in order to achieve a better understanding of the entire process. Once the processes are better understood, design charts and rules of thumb based on the physics of the problem, can be developed for simplfying design.

Presently, an empirically based model, the DEPOSITS model, is being used to simulate pond performance. This is currently the most widely accepted and perhaps only model for pond modeling. Models used to obtain hydrographs and predict sediment yields are now heading away from empirical approaches and toward simulating the individual hydraulic or erosion processes with mathematical formulas and finite element schemes. This allows for the modeling of the inter-

action of the many individual processes involved.

RESEARCH NEEDS

The following list of research needs was compiled during this study from the opinions expressed by individuals within the field. The research needs listed range from specific research on instruments, structures and methods to general information and data about erosion processes and sediment, to the development or refinement of sediment yield predictive equations and methods.

1. Develop an automatic, depth-integrating sampler that can be used in remote facilities.[66]

2. Research to improve effectiveness of baffles is needed.[127]

3. More research is needed on the use of coagulants and flocculants especially in cold weather.[128]

4. Study the characteristics of waterborne sediment loads.[120]

5. Develop a classification system for sediment similar in nature to the existing soil classification method.[35]

6. "Field measurements should be made on the quantitative effects of vegetative cover on reducing raindrop splash erosion, and the effects of vegetal stem density on infiltration rates and hydraulic roughness."[121]

7. In order to develop more conceptually sound sediment yield models, more research into the process of soil erosion and crop growth, and the influence of soil moisture on both, is needed.[123]

8. "More research work is needed to develop quantitative data and comparisons of the actual 'effectiveness' of most conservation measures."[49]

9. Data collection procedures need to be standardized.[127]

10. A method needs to be developed to predict sediment characteristics based on the known soil characteristics of land prior to disturbance.[127, 128]

11. "Relate seasonal vegetation cover and land use parameters derived from satellite multispectral scanner data to soil erosion, and modify existing equations or develop new equations that contain such parameters for predicting soil loss."[119]

12. Develop a method to select reasonable parameters for erosion relations by physical measurement of spoil or topsoil material, so that an accurate hydraulic erosion relation can be obtained.[121]

13. Collect data to verify values for the length/slope factor in the USLE for steep slopes.[49]

14. "Additional research and field evaluation should be devoted to constantly refining the equation (USLE) to meet needs expressed from the field and to gain improved understanding of its use and application."[48]

15. Develop a more physically based model than the USLE to achieve a better ability to distinguish between the effects of various treatments and topographies.[121]

16. Predictive equations are needed which will more accurately determine sediment concentrations and volumes reaching trap structures.[122]

17. Determine a method to predict the expected extent of rill formation for a given slope and soil.[121]

18. The suitability of the USLE and existing runoff models for use in surface mined areas needs to be established.[127]

19. Research is needed to verify that the MUSLE is applicable to most small watersheds.[55]

RECOMMENDATIONS

Based on the results of this study, the following recommendations are presented:

1. The effluent standards, as required by OSM, should be reviewed for applicability. The review should consider the differences in hydrologic conditions, soil type and topography that exist in the different geographical locations throughout the United States. Consideration should also be given to the existing

water quality of the receiving water, as well as the SS concentrations of runoff from undisturbed land.

2. Methods of collecting and reporting sediment properties and characteristics need to be standardized. In addition, a standardized method for determining and reporting SS concentrations needs to be established so that results of different studies can be correlated.

3. More research effort needs to be directed towards the application and use of chemical coagulants. In addition to research on the chemical processes and environmental impacts, reliable methods of physically applying the chemicals at the correct dosage rates for variations in flow rates and sediment concentrations need to be developed.

4. Effort should be directed towards developing a physically based model to simulate the hydraulic and sediment transport phenomena which occurs within sediment ponds.

APPENDIX

This appendix lists the agencies, universities, and consultants which were contacted for information during the course of this study.

1. <u>United States Department of Agriculture - SEA</u>

A. Federal Research
Southern Region
USDA Sedimentation Laboratory
Airport Road
P.O. Box 1157
Oxford, Mississippi 38655

B. Roger E. Smith
Agricultural Research
Western Region
Engineering Research Center
CSC Foothills Campus
Fort Collins, Colorado 80523

C. Gerald E. Schuman
Agricultural Research
Western Region
High Plains Grasslands
Research Station
Rt. 1, Box 698
Cheyenne, Wyoming 82001

D. J.A. Bondurant
Agricultural Research
Western Region
Snake River Conservation Research Center
Rt. 1, Box 186
Kimberly, Idaho 83341

E. Richard Phillips
SCS, Engineering Division
269 Federal Center
Hyattsville, Maryland 20782

F. James V. Bonta
Agricultural Research
North Appalachian Experimental Watershed
Coshocton, Ohio 43812
(614) 545-6349

2. <u>United States Department of the Interior</u>

A. James W. Spotts
Office of Surface Mining
Reclamation And Enforcement
818 Grand Ave., Scarritt Building
Kansas City, Missouri 64106
(816) 374-5109

B. Jesse Jackson
Office of Surface Mining
Reclamation and Enforcement
950 Kanawha Blvd., East
Charleston, W.V. 25301

C. USGS National Center
Reston, Va. 22092

D. Robert C. Glazier
Office of Surface Mining
Reclamation and Enforcement
Federal Building and U.S. Courthouse
46 East Ohio St.
Indianapolis, Indiana 46204

E. Roger C. Wilmoth, John Martin
United States Environmental Protection Agency
Extraction Technology Branch
Industrial Environmental Research Laboratory
5555 Ridge Ave.
Cincinnati, Ohio 45268
(513) 684-4417

F. Lewis NcNay, Don Smith
Office of Surface Mining
1951 Constitution Ave. N.W.
Washington D.C. 20240
(202) 343-2184

3. <u>United States Department of Energy</u>

A. Andrew A. Sobek
Argonne National Laboratory
9700 South Cass Ave.
Argonne, Illinois 60439
(312) 972-3358

4. <u>State Government Agencies</u>

A. Benjamin C. Greene
West Virginai Surface Mining and Reclamation Ass.
1624 Kanawha Blvd., East
Charleston, W. V.
(304) 346-5318

B. Cathy Epp
Ohio Department of Natural Resources
Fountain Square
Columbus, Ohio 43215
(614) 466-4850

5. Universities

A. C.T. Haan
Department of Agricultural Engineering
Oklahoma State University
Stillwater, Oklahoma 74074
(405) 624-5431

B. William Sack
West Virginia University
Morgantown, W.V. 26506

C. Andy Ward
Department of Agricultural Engineering
University of Kentucky
Lexington, Kentucky 40546

6. Engineering Consultants

A. Evan Nelms
Consolidation Coal Company
Midwestern Region
Cadiz, Ohio 43907

B. Charles E. Ettinger
Skelly and Loy
2601 North Front St.
Harrisburg, Pennsylvania 17110
(717) 232-0593

C. Ted Canfield
Water, Soil Control, Inc.
P.O. Box 411
New Philadelphia, Ohio 44663
(216) 339-3944

D. Paul D. Nesbitt
Nesbitt Engineering, Inc.
400 E. Vine St.
Suite 310
Lexington, Kentucky 40507
(606) 233-3111

REFERENCES

1. Riley, C.V., "Ecology-Ally of Mined Land Restoration," Second Research and Applied Technology Symposium on Mined-Land Reclamation, Louisville, Kentucky, October 22-24, 1974.

2. Jones, D.C., "Our Energy Crisis--The Electrical Power Dilemma," Coal Mining and Processing, 9(1): 36, 1972.

3. Durham, J.T., C. Rampacek, T.A. Henrie, "High Sulfur Coal for Generating Electricity," Science, 184 (4134) 346-351, 1974.

4. Overton, J.A. Jr., "From the Earth: Abundant Energy," Coal Mining and Processing, 11(4): 43, 1974.

5. Bagge, C., "NAE Report Staggering," Coal Mining and Processing, 11(7): 16, 1974.

6. Poe, E., "Coal and the Political Arena," Coal Mining and Processing, 11(1): 40, 1974.

7. Collier, C.R., R.J. Pickering, J.J. Musser, "Influences of Strip-Mining on the Hydrologic Enviroment of Parts of Beaver Creek Basin, Kentucky," U.S. Geol. Survey Prof. Paper, 427-C, 1970.

8. Curtis, W.R., "Strip-Mining, Erosion and Sedimentation," Trans. ASAE, 14(3): 434-436, 1971.

9. Highfill, R.E., L.W. Kimberlin, "Current Soil Erosion and Sediment Control Technology for Rural and Urban Lands," Proceedings of the National Symposium on Soil Erosion and Sedimentation by Water, Chicago, Illinois, December 12-13, 1977.

10. ASCE, Sedimentation Engineering, edited by Vita A. Vanoni, American Society of Civil Engineers, 1975.

11. Gessler, J., Research Needs as Related to the Development of Sediment Standards in Rivers, Completion Report Series No. 60, Colorado State University, Fort Collins, Colorado, 1975.

12. Hill, R.D., "Sediment Control and Surface Mining," Polish-U.S. Symposium, Environmental Protection in Openpit Coal Mining, Denver, Colorado, May, 1975.

13. Heft, F.E., "Political, Social, and Economic Aspects of Soil Erosion and Sedimentation Control Programs," Proceedings of the National Symposium on Soil Erosion and Sedimentation by Water, Chicago, Illinois, December 12-13, 1977.

14. Federal Register, 1977, Tuesday, March 13, Vol. 44- No. 50.

15. "Rainfall Intensity-Duration-Frequency Curves," U.S. Department of Commerce Weather Bureau, Technical Paper No. 25.

16. Haan, C.T., B.J. Barfield, Hydrology and Sedimentology of Surface Mined Lands, University of Kentucky, Lexington, Kentucky, 1978.

17. Horton, R.E., "An Approach Toward a Physical Interpretation of Infiltration Capacity," Proceedings, Soil Science Society of America, 5: 399-417, 1940.

18. Linsley, R.K., M.A. Kohler, J.L.H. Paulhus, Hydrology for Engineers, Second Edition, MsGraw-Hill, New York, 1975.

19. Willis, J.C., A.J. Bowie, D.A. Parson, "Sediment Yield Estimates Based on Floodwater Measurement and Samples," Proceedings, Mississippi Water Resources Conference, 1973.

20. Renard, K.G., E.M. Laursen, "Dynamic Behavior Model of Ephemeral Stream," J. Hydraul. Div. ASCE, 101 (HT5), 511-528, 1975.

21. Bruce, R.R., L.A. Harper, R.A. Leonard, W.M. Snyder, A.W. Thomas, "A Model for Runoff of Pesticides from Small Upland Watersheds," J. Environ. Qual., 4(4), 541-548, 1975.

22. Rendon-Herrero, O., "Unit Sediment Graph," Water Resources Research, Vol. 14, No. 5, October, 1978.

23. Williams, J.R., "A Sediment Graph Model Based on an Instantaneous Unit Sediment Graph," Water Resources Research, Vol. 14, No. 4, August, 1978.

24. Wisler, C.O., E.F. Brater, Hydrology, Second Edition, John Wiley and Sons, Inc., New York, 1959.

25. Wanielista, M.P., Stormwater Management Quantity and Quality, Ann Arbor Science Publishers Inc., 1978.

26. Tchobanoglous, G., Wastewater Engineering: Treatment, Disposal, Second Edition, Metcalf and Eddy, Inc., 1979.

27. Skelly and Loy, Development of Methods to Improve Performance of Surface Mine Sediment Basins, Phase 1, Contract No. 68-03-2677, February, 1979.

28. Robinson, A.R., "Sediment: Our Greatest Pollutant?" Agricultural Engineering, Vol. 53, No. 8, August, 1971.

29. McHenry, J.R., A.R. Robinson, "Sediment Research in Mississippi: Progress and Goals," Proceeding, Mississippi Water Resources Conference, 1974.

30. Lund, L.J., D. Kohnke, M. Paulet, "An Interpretation of Reservoir Sedimentation II, Clay Mineralogy," J. Environ. Quality, 3: 303-307, 1974.

31. Willis, J.C., A.J. Bowig, D.A. Parson, "Sediment Yield Estimates Based on Floodwater Measurement and Samples," Proceedings, Mississippi Water Resources Conference, 1973.

32. Fair, G.M., J.C. Geyer, D.A. Okun, Water and Wastewater Engineering, Wiley, New York, 1971.

33. Davis, S.S., G.R. Foster, L.F. Huggins, "Deposition of Non-Uniform Sediment on Concave Slopes." Winter Meeting ASAE, Illinois, December 18-20, 1978.

34. Ward, A.D., C.T. Haan, J. Tapp, The DEPOSITS Sedimentation Pond Design Manual, University of Kentucky, Lexington, Kentucky, 40546, 1979.

35. Meier, M.C., "Research Needs in Erosion and Sediment Control," Soil Erosion: Prediction and Control, Soil Conservation Society of America, Ankeny, Iowa, May, 1976.

36. National Handbook of Recommended Methods for Water-Data Acquisition, United States Department of the Interior, 1979.

37. Kathuria, D.V., M.A. Nawrocki, B.C. Becker, Effectiveness of Surface Mine Sedimentation Ponds, EPA-600/2-76-117, August, 1976.

38. Foster, G.E., L.D. Meyer, "Soil Erosion and Sedimentation by Water-An Overview," Proceedings, National Symposium on Soil Erosion and Sedimentation by Water, Chicago, Illinois, December 12-13, 1977.

39. Vanoni, V.A., Sediment Engineering, American Society of Civil Engineers, 1975.

40. SEA-USDA, "Predicting Rainfall Erosion Losses," A Guide to Conservation Planning, Supersedes Agriculture Handbook No. 282, 1978.

41. Jens, S.W., "Drainage of Airport Surfaces-Some Basic Design Conditions," ASCE Trans., Vol 113, 1948.

42. Wischmeier, W.H., C.B. Johnson, B.V. Cross, "A Soil Erodibility Nomograph for Farmland and Construction Sites," Journal Soil Water Conservation, 26(5): 189-193, 1971.

43. Romkens, M.J., C.B. Roth, D.W. Nelson, "Soil Erosion on Selected High Clay Subsoils," Journal Soil and Water Conservation, 30: 173-176, 1975.

44. Singer, M.J., J. Back, E. Gillogley, K. Arulanandan, "Engineering and Pedological Properties of Soils as They Affect Erodibility." Contribution No. 166, California Water Resources Center, University of California, Davis, California, 1978.

45. Levesey, R.H., "Corps of Engineers' Methods for Predicting Sediment Yield," Proceedings, Sediment-Yield Workshop, USDA Sedimentation Laboratory, Oxford, Mississippi, November 28-30, 1972.

46. Holeman, J.N., "Procedures Used in the Soil Conservation Service to Estimate Sediment Yield," Proceedings, Sediment-Yield Workshop, USDA Sedimentation Laboratory, Oxford, Mississippi, Novermber 28-30, 1972.

47. EPA , Methods for Identifying and Evaluating the Nature and Extent of Nonpoint Sources of Pollutants, EPA-430/9-73-014, Washington, D.C., October, 1973.

48. Kimberlin, L.W., W.C. Moldenhauer, "Predicting Soil Erosion," Proceedings, National Symposium on Soil Erosion and Sedimentation by Water, Chicago, Illinios, December 12-13, 1977.

49. EPA, Comparative Costs of Erosion and Sediment Control, Construction Activities, EPA-430/9-73-016, U.S. Environmental Protection Agency, Office of Water Program Operation, Washington, D.C., July, 1973.

50. Onstad, C.A., C.K. Mutchler, A.J. Bowie, "Predicting Sediment Yield," Proceedings, National Symposium on Soil Erosion and Sedimentation by Water, Chicago, Illinois, December 12-13, 1977.

51. Heinemann, H.G., R.F. Piest, "Soil Erosion--Sediment Yield Research in Progress," EOS, Transactions, American Geophysical Union, Vol. 56, No. 3, March, 1975.

52. Wischmeir, W.H., D.D. Smith, "Rainfall Erosion Losses from Cropland East of the Rocky Mountains," Agriculture Handbook No. 282, U.S. Department of Agriculture, Washington, D.C., 1965.

53. "Use and Misuse of the Universal Soil Loss Equation," Journal of Soil and Water Conservation, 31(1): 5-9, 1976.

54. Ragoff, M.J., "Use of the Universal Soil Loss Equation in Water Quality Assessment: An Annotated Bibliograph," Council of Planning Librarians, Exchange Bibliography, 1498, April, 1978.

55. Williams, J.R., "Sediment-Yield Prediction with Universal Equation Using Runoff Energy Factor," Proceedings, Sediment-Yield Workshop, USDA Sediment Laboratory, Oxford, Mississippi, November 28-30, 1972

56. Williams, J.R., H.D. Berndt, "Sediment Yield Prediction Based on Watershed Hydrology," Trans. ASAE, Vol.20, No. 6, 1977.

57. Call, C.E., Letter of Instruction from the Ohio Department of Natural Resources to all Ohio coal strip mine operators, Columbus, Ohio, July 23, 1979.

58. Brown, H.E., E.A. Hansen, N.E. Champagne Jr., "A System for Measuring Total Sediment Yield from Small Watersheds," Water Resources Research, Vol. 6, No.3, June, 1970.

59. Heinemann, W.H., M.J. Brown, "Fractional Water-Sediment Sampler," Soil Science Society of America, Vol. 36, 1972.

60. Carter, C.E., D.A. Parsons, "Field Tests on the Coshocton-Type Wheel Runoff Sampler," Trans. ASAE, Vol. 10, No. 1, 1967.

61. Wang, J.Y., R.E. Hermanson, J.G. Hendrick, "Modification of H-Flume and Coshocton Wheel System," Trans. ASAE, Vol. 14, No. 6, 1971.

62. Swanson, N.P., "A Programmed Sampler for Runoff and Bedloads," Trans. ASAE, Vol. 6, No. 4, 1973.

63. Jarocki, W., A Study of Sediment, Centralny Instytut Informacji, Naukowo-technicznej i Ekonomicznej, Warszawa, Poland, 1963.

64. Witzigman, F.S., "A Summary of the Work of the Inter-Agency Sedimentation Project," Proceedings, Second Federal Inter-Agency Sedimentation Conference, 1963.

65. Walling, D.E., "Assessing the Accuracy of Suspended Sediment Rating Curves for a Small Basin," Water Resources Research, Vol. 13, No. 3, June, 1977.

66. Becker, B.C., D.B. Emerson, M.A. Nawrock, Joint Construction Sediment Control Project, EPA-660/2-73-035, Washington, D.C., 1974.

67. Curtis, W.R., "Sediment Yield from Strip-Mined Watersheds in Eastern Kentucky," Second Research and Applied Technology Symposium on Mined-Land Reclamation, October, 1974.

68. Grim, E.C., R.D. Hill, Environmental Protection in Surface Mining of Coal, EPA-670/2-74-093, October, 1974.

69. EPA, Erosion and Sediment Control Surface Mining in the Eastern U.S., EPA-625/3-76-006 (Design, Planning), October, 1976.

70. Amimoto, P.Y., Erosion and Sediment Control Handbook, EPA-440/3-78-003, Department of Conservation, Resources Agency, State of California, May, 1978.

71. Water Resources Administration, State of Maryland and Hittman Associates, Inc., Guidelines for Erosion and Sediment Control Planning and Implementation, EPA-R2-72-015, August, 1972.

72. New Jersey State Soil Conservation Committee, Standards for Soil Erosion and Sediment Control in New Jersey, 1972.

73. Howard, G.S., G.E. Schuman, F. Rauzi, "Growth of Selected Plants on Wyaming Surface-Mined Soils and Flyash," Journal of Range Management, Vol. 30, No. 4, July, 1977.

74. Schuman, G.E., E.M. Taylor, "Use of Mine Spoil Material to Improve the Topsoil," People Crops Soils Livestock Research Journal 130, 1978.

75. Konya, C.J., "Mined Land Reclamation by Biological Reactivation," Research Proposal, Mining and Mineral Resources Research Institute, The Ohio State University, July, 1979.

76. Ruffner, J.D., "Plant Performance on Surface-Mine Spoil in the Eastern United States," New Directions in Century Three: Strategies for Land and Water Use, Proceedings, 32nd Annual Meeting, Soil Conservation Society of America, Richmond, Virginia, August, 1977.

77. Department of Natural Resources, State of Michigan, Michigan Soil Erosion and Sedimentation Control Guidebook, February, 1975.

78. Kao, D.T.Y., B.J. Barfield, "Prediction of Flow Hydraulics for Vegetated Channels," Trans. ASAE, Vol. 21, No. 3, pp. 489-494, 1978.

79. Moore, W.R., C.E. Smith, "Erosion Control in Relation to Watershed Management," Irrig. and Drain. Div. ASCE, September, 1968.

80. Farmer, E.E., Z. Richardson, "Hydrologic and Soil Properties of Coal Mine Overburden Piles in Southeastern Montana," 4th Symposium on Surface Mining and Reclamation, October, 1976.

81. Noble, E.L., "Sediment Reduction Through Watershed Rehabilitation," Proceedings, Second Federal Inter-Agency Sediment Conference, 1963.

82. Alberts, E.E., G.E. Schuman, R.E. Burwell, "Seasonal Runoff Losses of Nitrogen and Phosphorus from Missouri Valley Loss Watersheds," Journal of Environmental Quality, Vol. 7, No. 2, April-June, 1978.

83. Laflen, J.M., H.P. Johnson, R.O. Hartwig, "Sediment Modeling of Impoundment Terraces," Trans. ASCE, 1977.

84. Mills, T.R., "Erosion and Sediment Control During Surface Mining in the Eastern United States," 6th Symposium on Coal Mine Drainage Research, 1976.

85. Barfield, B.J., T.Y. Kao, Analysis of the Sediment Filtering Action of Grass Media, Research Report No. 90, University of Kentucky, Water Resources Research Institute, Lexington, Kentucky, 1975.

86. Kao, D.T., B.J. Barfield, A.E. Lyons, Hydraulic Resistance of Grass Media on Shallow Overland Flow, Research Report No. 108 University of Kentucky, Water Resources Research Institute, Lexington, Kentucky, 1977.

87. Tollner, E.W., B.J. Barfield, C.T. Haan, "Vegetation as a Sediment Filter," Proceedings, National Symposium on Urban Hydrology and Sediment Control, University of Kentucky, Lexington, Kentucky, July 28-31, 1975.

88. Kao, D.T.Y., B.J. Barfield, A.E. Lyons, Jr., "On-Site Sediment Filtration Using Grass Strips," Proceedings, National Symposium on Urban Hydrology and Sediment Control, University of Kentucky, Lexington, Kentucky, July 28-31, 1975.

89. Kao, D.T.Y., A.E. Lyons, B.J. Barfield, "Potential Application of Vegetative Filter for Mine Drainage Sediment Control," 6th Symposium on Coal Mine Drainage Research, October, 1976.

90. Hazen, A., "On Sedimentation," Trans. ASCE, Vol. 53, December, 1904.

91. Ingersoll, A.C., J.E. McKee, N.H. Brooks, "Fundamental Concepts of Rectangular Settling Tanks," Trans. ASCE 121, 1179, 1956.

92. Nawrocki, M.A., "SS Removal, How Effective Are Sediment Ponds?" Water and Wastes Engineering, Vol. 15, No. 9, 1978.

93. Murray, S.P., "Settling Velocities and Vertical Diffusion of Particles in Turbulent Water," J. Geophysical Res., Vol. 75, No. 9, 1970.

94. USDA, SCS, Water Management and Sediment Control for Urbanizing Areas, Columbus, Ohio, June, 1978.

95. Oscanyan, P.C., "Design of Sediment Basins for Construction Sites," Proceedings, National Symposium on Urban Hydrology and Sediment Control, University of Kentucky, Lexington, Kentucky, July 28-31, 1975.

96. Ward, A.D., C.T. Haan, "Evaluation of Stripmine Sediment Detention Basins in Kentucky," Paper for Presentation at 1978 Winter Meeting, American Society of Agricultural Engineers, December 18-21, 1978.

97. Haan, C.T., "A Dimensionless Hydrograph Equation," File Report, Agricultural Engineering Department, University of Kentucky, Lexington, Kentucky, 1970.

98. McCarthy, R.E., "Surface Mine Siltation Control," Mining Congress Journal, June, 1973.

99. Boysen, S.M., Development and Application of Sediment Basins in Maryland, Presented at the 1978 Winter Meeting of ASAE, Chicago, Illinois, December, 18-20, 1978.

100. Bondurant, J.A., C.E. Brockway, M.J. Brown, "Some Aspects of Sedimentation Pond Design," Proceedings, National Symposium on Urban Hydrology and Sediment Control, University of Kentucky, Lexington, Kentucky, July 28-31, 1975.

101. Bondurant, J.A., "Erosion and Sedimentation on Irrigated Lands," Proceedings, National Symposium on Soil Erosion and Sedimentation by Water, Chicago, Illinoiw, December 12-13, 1977.

102. Glazier, R., OSM Indianapolis, Indiana, Telephone Conversation, September 20, 1979.

103. Linderman, C.L., N.P. Swanson, L.N. Mielike, "Riser Intake Design for Settling Basins," Trans. ASAE, Vol. 19, No. 5, 1976.

104. Jenkins, C.R., J.F. Pankanin, "Modification of Sediment Control Ponds," Presented at the 34th Purdue Industrial Waste Conference, May 8-10, 1979.

105. Ward, A.D., C.T. Haan, B.J. Barfield, "The Design of Sediment Basins," Paper Presented at 1978 Summer Meeting, ASAE, Utah State University, Logan Utah, June 27-30, 1978.

106. EPA, Process Design Manual for Suspended Solids Removal, USEPA Technology Transfer EPA 625/1-75-003a, 1975.

107. Bonta, J.V., USDA-SEA, Agricultural Research, Coshocton, Ohio, Telephone Conversation, September, 1979.

108. Young, R.A., C.A. Onstad, "Predicting Particle-Size Composition of Eroded Soil," Trans. ASAE, 19(6), 1976.

109. Chukwuma, G.O., W.H. Edwards, G.O. Schwab, "Rainfall-Runoff Factor for Soil Loss from Small Watersheds," Paper Presented at the 1979 Summer Meeting of ASAE and CSAE, University of Manitoba, Winnipeg, Canada, June 24-27, 1979.

110. Ricca, V.T., The Ohio State University Version of the Stanford Streamflow Simulation Model, State of Ohio Water Resources Center, Ohio State University, June, 1974.

111. Meyer, L.D., W.H. Wischmeier, "Mathematical Simulation of the Process of Soil Erosion by Water," Trans. ASAE, 12(6), 1969.

112. David, W.P., C.E. Beer, "Simulation of Soil Erosion-Part I. Development of a Mathematical Erosion Model," Trans. ASAE 18(1), 1975.

113. Onstad, C.A., G.R. Foster, "Erosion Modeling on a Watershed," Trans ASAE 18(2), 1975.

114. Foster, G.R., L.D. Meyer, C.A. Onstad, "Erosion Equations Derived from Modeling Principles," ASAE Paper No. 73-2550, ASAE, St. Joseph, Michigan, 49085, 1973.

115. David, W.P., C.E. Beer, "Simulation of Soil Erosion-Part II. Streamflow and Suspended Sediment Simulation Results," Trans. ASAE 18(1), 1975.

116. Li, Ruh-Ming, "Water and Sediment Routing from Small Watersheds," Proceedings, Third Federal Inter-Agency Sedimentation Conference, Denver, Water Resources Council, 1976.

117. Clar, M., "Sedimentation Control: Implications of EPA Effluent Limitation Guidelines on Current Design Practice," Society of Mining Engineers of AIME, Salt Lake City, Utah, Preprint No. 77-F-376, 1977.

118. Young, R.L., "Above Lake Needwood," Trends in Park Recreation, January/February, 1970.

119. Robinson, A.R., L.D. Meyer, "The Agricultural Research Service National Research Program on Soil Erosion by Water," Soil Erosion: Prediction and Control, Soil Conservation Society of America, Ankeny, Iowa, May, 1976.

120. Ward, A.D., D.L. Rausch, C.T. Haan, H.G. Heinemann, "A Verification Study on a Sediment Basin Model," Paper Presented at the 1979 Summer Meeting of ASAE and CSAE, University of Manitoba, Winnipeg, Canada, June 24-27, 1979.

121. Smith, R.E., D.A. Woolhiser, "Some Applications of Hydrologic Simulation Models for Design of Surface Mine Topography," The Reclamation of Disturbed Arid Lands, University of New Mexico Press, Albuquerque, New Mexico, 1978.

122. Ward, A.D., C.T. Haan, B.J. Barfield, "The Performance of Sediment Detention Structures," Proceedings, International Symposium on Urban Hydrology, Hydraulics, and Sediment Control, University of Kentucky, Lexington, Kentucky, July 18-21, 1977.

123. DeCoursey, D.G., L.D. Meyer, "Philosophy of Erosion Simulation for Land Use Management," Soil Erosion: Prediction and Control, Soil Conservation Society of America, Ankeny, Iowa, May, 1976.

124. EPA, Current Projects, Extraction Technology Branch, Resource Extraction and Handling Division, Industrial Environmental Research Laboratory, Cincinnati, Ohio, 1979.

125. Vogel, W.G., "Revegetation Research on Surface-Mined Land in Eastern Kentucky," Proceedings, Fourth Kentucky Coal Refuse Disposal and Utilization Seminar, Lexington, Kentucky, June 6-7, 1978.

126. Davis, W.J., W.E. Bell, L.H. Williams, "Trap Efficiency of Sediment Basins Below Construction Sites- A Practical Case Study," Proceedings, International Symposium on Urban Hydrology, Hydraulics, and Sediment Control, Lexington, Kentucky, July 18-21, 1977.

127. Ward, A.D., University of Kentucky, Lexington, Kentucky, Personal Conversation, May 10, 1979.

128. Nesbitt, P.D., Lexington, Kentucky, Personal Conversation, May 11, 1979.

129. Wu, T.H., The Ohio State University, Personal Conversation, November 5, 1979.

130. Holtan, H.N., N.C. Lopez, USDAHL-70 Model of Watershed Hydrology, Technical Bulletin No. 1435, ARS, USDA, November, 1971.

131. Huggins, L.F., E.J. Monke, Technical Report No. 1, Purdue University, Water Resources Center.

132. Nesbitt, P.D., A. Notary, "Hydrologic Design of Sediment Dams Under Office of Surface Mining Regulations," Paper Presented at The Federal Surface Mining Regulations Conference, Washington, D.C., March 12, 1979.

133. Lavelle, J.W., R.A. Young, D.J. Swift, T.L. Clarke, "Near-Bottom Sediment Concentration and Fluid Velocity Measurements on the Inner Continental Shelf, New York," Journal of Geophysical Research, Vol. 83, No. C12, December 20, 1978.

134. GO General Equipment & Manufacturing Co., Inc., 3300 Fern Valley Road, Louisville, Kentucky.

135. Wolman, M.G., "Changing Needs and Opportunities in the Sediment Field," Water Resources Research, Vol. 13, No. 1, February, 1977.